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REDUCTION TECHNOLOGY (NASA)

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**NASA TECHNICAL  
MEMORANDUM**

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**AIRCRAFT NOISE REDUCTION TECHNOLOGY**

Lewis Research Center  
Cleveland, Ohio  
March 1973

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16. Abstract <p>This report, describing the NASA noise reduction technology programs and plans, was prepared for use by the Environmental Protection Agency in the aircraft/airport noise study. Separate sections of the report deal, respectively, with characterizing the effects of aircraft noise on individuals and communities; the status of aircraft source noise technology; operational procedures to reduce the impact of aircraft noise; and aspects of NASA relations with the military services in the aircraft noise area. The report is a summary and guide to aircraft noise research and technology and includes references to more detailed technical literature on the subjects discussed.</p>		
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## FOREWORD

The Environmental Protection Agency has requested the participation of the National Aeronautics and Space Administration in a comprehensive study of the noise problems resulting from aircraft operations. This study is being conducted by EPA in consultation with federal, state, and local agencies and other interested persons. The results of the study will be contained in an EPA report to be submitted to the Congress as directed by the Noise Control Act of 1972 (PL 92-574).

As a part of the support requested, NASA has prepared this preliminary report for use by EPA in the aircraft/airport noise study. The intent of this report is to describe the NASA noise reduction technology programs and plans. To put the NASA program in context, the general status of noise reduction technology is described. The major problems to be overcome in reducing the noise generated by the various noise sources are discussed. The gains that have been made in noise technology are included, and the associated penalties in performance and the economic penalties are provided where known. It must be emphasized, however, that this is chiefly a technology report and that the practicability of using this technology in actual aircraft systems involves detailed consideration of performance and economics for each individual application.

The EPA Task Group topics in this report are impact characterization, source abatement technology, flight operations, and military aspects. Each topic is addressed in a separate section.

Section I of the report discusses the problem of characterizing the impact of aircraft noise on the individuals and communities affected. The capability of various parameters and methods for accurately estimating the psychoacoustical impact on individuals and communities is assessed. The difficulties associated with the effective use of the various impact characterizations are discussed. The unique characteristics of the sonic boom and the interpretation of its impact on the community is reviewed.

In section II the broad subject of noise abatement technology is covered. The status of noise technology in the various propulsion system component areas is described. The relative importance of the component noise sources for the different aircraft applications, subsonic, supersonic, and powered lift aircraft, is discussed. The results of the NASA Quiet Engine Program are presented. The direction of future NASA source noise reduction research is also indicated.

Section III is concerned with the use of operational procedures to reduce the impact of aircraft noise. Primary emphasis is on the current NASA Two-Segment Approach Program. The potential noise benefits are indicated, and the results to date are described. Future plans for this activity are also given.

Finally, section IV deals with various aspects of the NASA relation with the military services in the aircraft noise area. Formal and informal agreements, mutual programs, and exchange of personnel are all a part of the effort to realize the maximum noise reduction benefits in the civil area from military research and development programs.

The NASA noise technology program is guided by a continuing study of various aircraft and propulsion systems, including conventional subsonic aircraft, supersonic aircraft, and powered-lift aircraft for short-haul applications. These studies are conducted in house as well as through contracts with industry and are often based on assumptions of future technology levels. Although quite useful as a guide to research and technology, the precise results of such studies are speculative. Therefore, specific details of the various studies that NASA has conducted do not appear here, although general trends are sometimes included.

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## I - IMPACT CHARACTERIZATION ANALYSIS

Basic to the effective control of aircraft noise and sonic boom is the development and validation of units of measurement that properly describe human response to them. Aircraft noise is of concern during ground operation, takeoff, climbout, and landing; whereas, sonic boom is of concern during the supersonic portion of flight over inhabited areas.

Included herein are brief discussions of NASA contributions to both noise and sonic boom characterization technology, the current state of the art, and some plans for future research. Specific mention is made of the research approaches used, the type of results obtained, and the manner of application of such information in aircraft noise control and its broader significance for community noise considerations.

### AIRCRAFT NOISE MEASUREMENTS

#### SUBJECTIVE RESPONSE

Accurate measurement units describing human response are needed to define noise specifications for quieter aircraft and for aircraft noise certification. Units which are simple in concept and easy to use are also needed in predicting community annoyance and complaint patterns, land-use planning near airports, and airport traffic monitoring and control.

The definition of the measurement units is influenced by the psychophysiological characteristics of people, as seen by their responses to noise; the physical characteristics of the aircraft noise stimuli; and aircraft operational data, which include airport traffic, preferential runways, mix of aircraft types, and flight scheduling (time of day); such community environment considerations, as background noise levels; economic, geographic, and demographic factors; and community activities.

NASA has supported studies to characterize and evaluate individual and community response to aircraft noise. These efforts have been involved in developing an understanding of how one perceives noise in degrees of noisiness and annoyance. Individual response to single noise producing events and the overall responses of communities to actual commercial aircraft operations were studied. This work has been accomplished largely under contract (refs. 1 to 8) by such organizations as Bolt, Beranek, and



Newman; Tracor, Inc.; Boeing Vertol; and Stanford Research Institute, and has been coordinated with other government agencies and the National Research Council through the active participation of CHABA.

The effects of noise on people may include annoyance, speech interference, sleep interference, degradation of task performance, and hearing losses. Although each of these effects can be important in particular circumstances, annoyance and sleep interference are judged to be of particular importance in understanding airport community situations and are thus focal points for NASA supported field and laboratory research in this area.

In a global sense it is recognized that all the above effects may contribute in some manner to shaping community attitudes; thus attempts have been made in a broad sense to correlate responses to noise exposure through the use of opinion poll surveys.

In the development and evaluation of measurement units, NASA studies used several test situations where environmental control was considered optimum. For example, many test situations involve a small anechoic room. A loudspeaker system is provided for playback of aircraft noise signals, and persons are arranged in a manner suitable for obtaining comparative subjective judgments of the noises. The advantage of such an experimental setup is that many of the physical factors in the tests are under very close control. The disadvantage, however, is that the environment lacks realism and thus may influence subjective judgment.

Another example is the field study which involves special flight operations arranged so that judgment data can be obtained. In one of these studies about a dozen different aircraft, including helicopters, were used, and subjects were located both outside and inside residence-type structures for subjective reaction studies. These studies were more realistic for the subjects but obviously did not completely represent real-life situations. Current, and future, testing for subjective responses are making use of improved capabilities for realistically simulating both indoor and outdoor noise exposure situations. The NASA sponsored Noise Research Laboratory at Columbia University and the Aircraft Noise Reduction Laboratory now under construction at the Langley Research Center will provide a high degree of environmental control for this type study.

Studies of noise induced sleep interference use electroencephalographic (EEG) measurements as an indicator of sleep state. These studies correlate the EEG pattern shift with the subject's noise exposure history during sleep. Realistic laboratory environments (Stanford Research Institute; North Carolina State University) are provided for the subjects who are exposed to various types and levels of aircraft noise. Currently the laboratory data are being supplemented by a study that is being conducted in actual homes near airports (refs. 10 to 14).

## MEASUREMENTS OF NOISINESS

Three general types of noisiness measurement units for flyover noise exposures have been proposed. They are characterized as maximum units, effective units, and composite units. The factors considered in defining these noise evaluation units can be further categorized as seen in figure I-1.

The maximum units include such measurements as A-scale, which along with a number of other similar units can be measured by a meter having an appropriate filter system. The function of the filter is to provide frequency weighting to represent the noisiness value of the noise. These units are useful in providing a quick determination of characteristic psychological responses of people to noise. Figure I-2 illustrates the significance of A-scale levels in dB(A) in traffic noise situations. Figure I-3 on the other hand provides comparative perceived noise levels at various distances for several types of transportation vehicles.

The effective units, on the other hand, are designed especially for aircraft noise certification. They incorporate such additional features of a single noise exposure as its audible pure tone content, the duration of exposure, and other significant aspects of its time history (fig. I-3). They are evaluated by a more sophisticated data analysis, which is usually performed by a computer. An example of an effective unit is the effective perceived noise level (EPNL). In studies to date, a number of effective units for noisiness measurements have been developed and evaluated.

Composite units are designed to represent the overall exposure, at a point or over an area, to series of noise events which occur during a given period of time. Thus, additional adjustment factors accounting for the number of overflights, the types of aircraft involved, and their operating schedules are incorporated. Computer programs are available to predict noise contours having equal values of such composite units as Composite Noise Rating (CNR) or Noise Exposure Forecast (NEF). Noise contours are useful in determining the ground areas and associated populations that receive given noise exposures. (See, for example, fig. I-4.) The ability to predict such noise contours can be an important consideration in land-use planning for airport communities. Valid contour predictions infer an understanding of such atmospheric effects as attenuation, scattering, and refraction, and the influence of terrain. Simplifying assumptions are usually made regarding all the above factors, and as a result prediction accuracy is degraded as distance is increased.

In order to evaluate these measurement units, NASA has supported several laboratory and flyover studies, which included some evaluations of the above units. For each of these studies, hundreds, or sometimes thousands, of judgments were made, and the results were evaluated against various measurement units. In these studies the effective units were generally the most accurate.

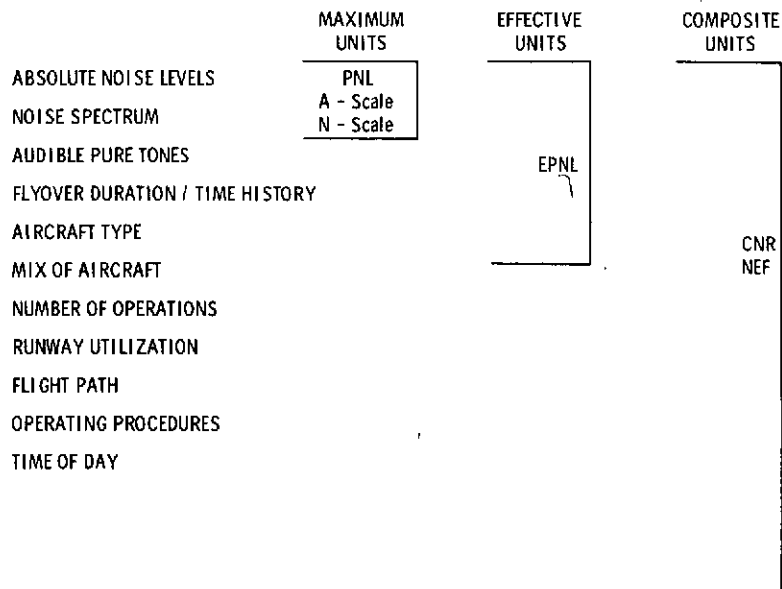


Figure I-1. - Characteristics of noise stimuli that are accounted for by various types of subjective evaluation units.

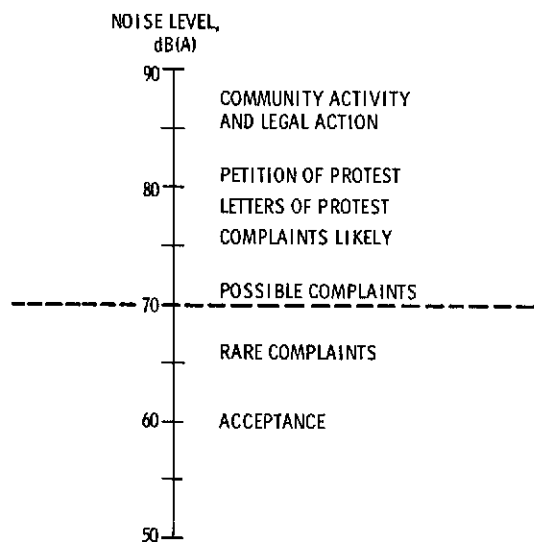


Figure I-2. - Estimated community responses for various levels of single event traffic noises (ref. 11).

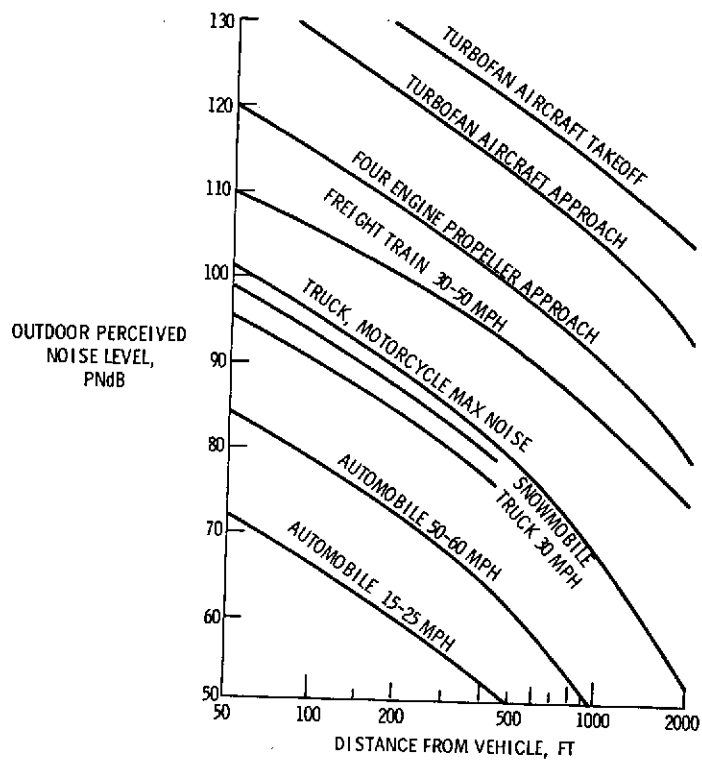


Figure I-3. - Example perceived noise level as a function of distance from several transportation vehicles (ref. 9).

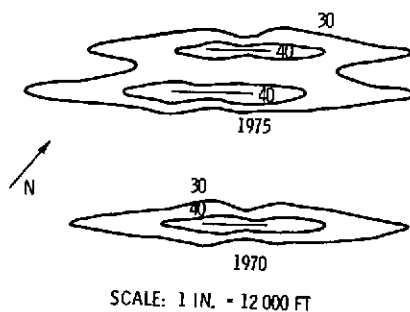


Figure I-4. - Noise exposure forecast (reference) contours for 1970 and 1975 operations at Raleigh-Durham, N.C., airport, reflecting effects of increases in traffic volume on exposed areas (ref. 8).

## COMMUNITY REACTION TO AIRCRAFT OPERATIONS

NASA has sponsored a number of community survey research studies to determine the manner in which people react to airport noise. This work has been accomplished through contract support of the National Opinion Research Center, the University of Chicago, Columbia University, and Tracor, Inc. In these studies, random sampling procedures have been employed to evaluate the reactions of people in various kinds of environments for which the noise exposures could be characterized. To date, studies have been conducted in nine airport communities for which the environmental situations varied widely. Both large and small cities were included in the study as well as noisy and relatively quiet neighborhoods.

The reactions of individuals to aircraft noise exposures were noted to correlate with several factors other than their noise environment. These nonnoise factors (which were interrelated with noise level) included fear of aircraft crashes, noise susceptibility, noise adaptability, misfeasance, and pollution annoyance. For all cities studied, pertinent data relating to those highly annoyed and to complainants are listed in table I-1. The percent of persons highly annoyed was always greater than the percent who complained, as is indi-

TABLE I-1. - ANNOYANCE AND COMPLAINT DATA  
DERIVED FROM INTERVIEWS IN AIRPORT  
COMMUNITIES OF NINE CITIES (REF. 8)

City	Number inter- viewed	Number highly annoyed	Percent highly annoyed	Number com- plainants	Percent com- plainants
CHI	872	299	34	43	4.9
DAL	923	236	26	22	2.4
DEN	1009	215	21	33	3.3
LAX	786	382	49	93	11.8
BOS	1166	517	44	156	13.4
MIA	676	148	22	12	1.8
NYC	1070	696	65	240	22.4
CHAT	1114	102	9.2	3	0.3
RENO	846	124	14.6	4	0.5

cated in figure I-5 which is plotted from the data of table I-1. Given the noise exposure (for CNR values between 85 and 125) and population density patterns for a community, the number of highly annoyed persons and complaints can be predicted (ref. 8). High annoyance was not detected in any of the test sites that had a CNR value of 85 or less. The CNR values corresponding to a high annoyance level for 20 percent of the surveyed population ranged from about 98 for the large cities to 115 for the small cities.

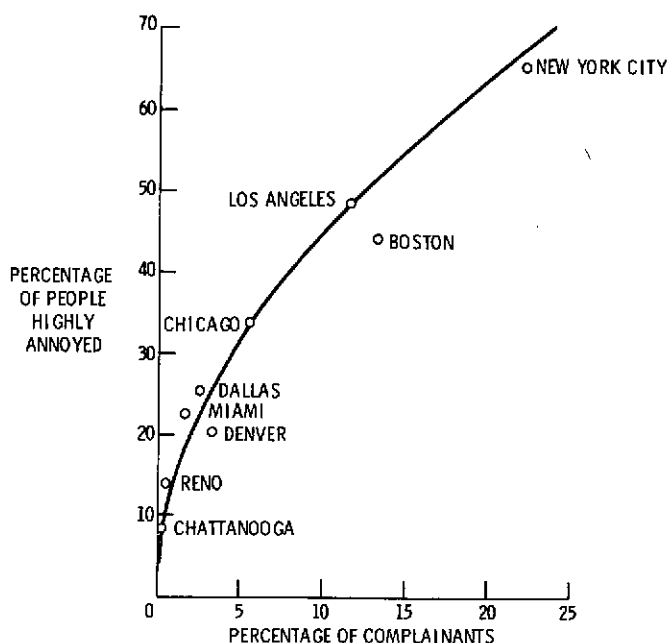


Figure I-5. - Relation between percentage of highly annoyed people and percentage of complainants in statistical samples of the population of nine cities.

## SONIC BOOM

The technology for sonic boom assessment has not been precisely developed; however, effort has been expended to characterize the statistical nature of the exposure. Important in this exposure is the variability from a true N-wave along with associated community and individual responses. NASA personnel have had a monitoring, supervising, or coordinating role in all major research projects relating to the effects of sonic booms on community response. Other agencies which participated actively and provided substantial resources are the Department of Defense, Department of Transportation, and the Department of Commerce.

Laboratory simulation studies, jury studies involving people both inside and outside residential structures, and actual supersonic overflights of entire communities for the purpose of evaluating human responses have been performed.

The sonic boom is unique among noise exposures because it is impulsive in nature, exposes very large areas nearly simultaneously, and comes without warning. It can have a direct effect on people who are exposed in an outdoor situation and a much different effect on those who are sheltered inside a building or other structure. Detrimental effects on buildings and on other possessions may in certain circumstances be very significant in shaping public opinion and in defining acceptance criteria. (See ref. 15.)

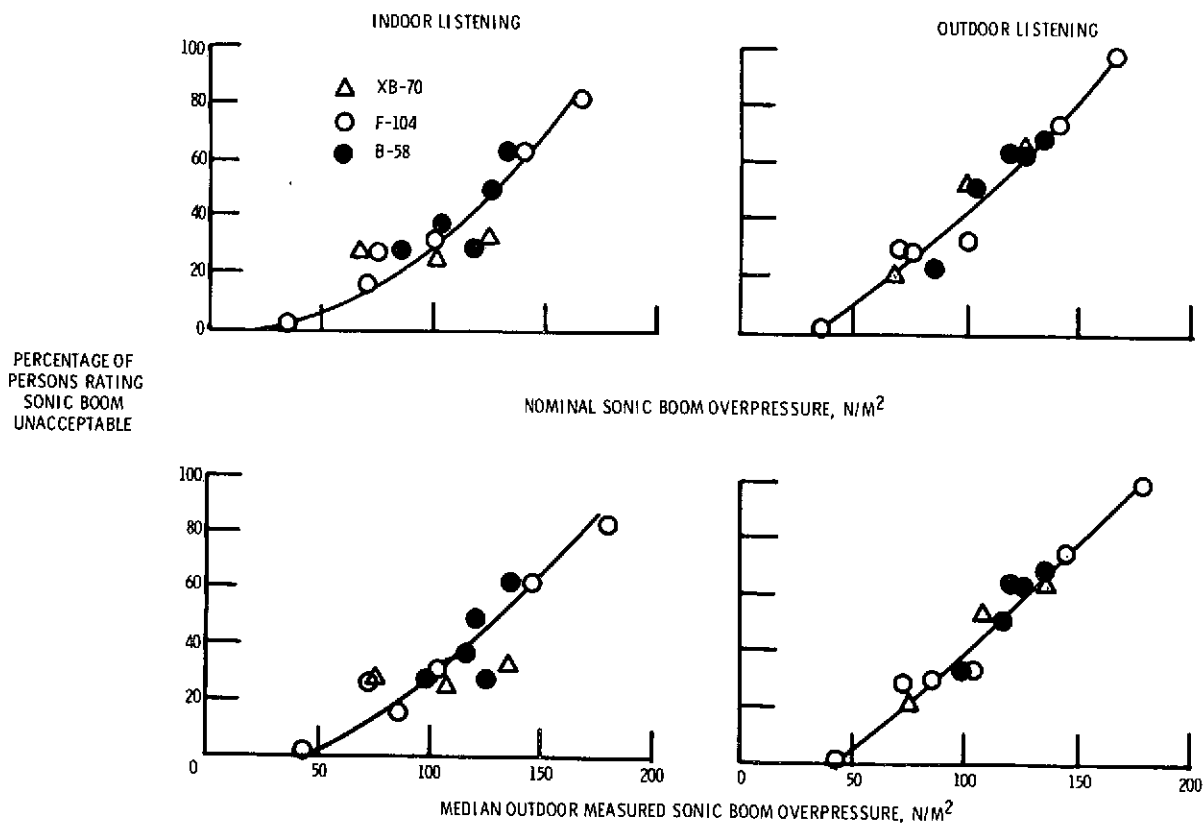


Figure I-6. - Percentage of people who rated as unacceptable sonic booms from XB-70, F-104, and B-58 aircraft. (Listeners from Edwards Air Force Base.) All aircraft were the first aircraft of a pair. Data from reference 14.

Acceptability of sonic booms with respect to annoyance for both inside and outside listening situations was studied using actual aircraft overflights, and the results are summarized in figure I-6. For a projected rate of 10 to 15 booms per day, the percentage of unacceptability ranges from virtually zero at measured peak overpressure of 36 newtons per square meter (0.75 lb/ft<sup>2</sup>) to virtually 100 percent at a peak overpressure of 172 newtons per square meter (3.6 lb/ft<sup>2</sup>). The causes of annoyance among those expressing more than a little annoyance during community flyover tests are divided into categories in figure I-7. Such factors as house rattles, startle, and interruption of sleep and rest are noted to be significant.

Studies of human response to sonic boom have identified the significant parameters of the boom pressure signature. Outdoor annoyance increases markedly as the "risk time" of the shocks decreases as well as with the degree of "spikiness" in the signature. Indoor annoyance, on the other hand, depends upon the loudness level, the degree of rattle and vibration and, among other things, whether the individual is a homeowner.

For all supersonic aircraft tested to date, neither rise time nor random spikiness

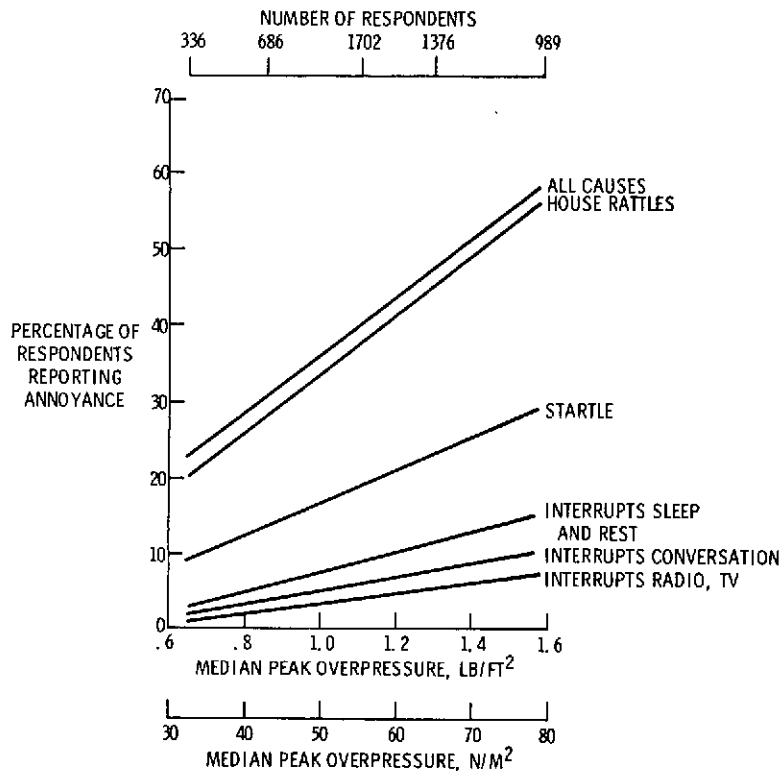


Figure I-7. - Factors contributing to annoyance due to various levels of sonic boom exposure during community overflights (ref. 14).

in the signature are controllable features; they depend on random atmospheric effects of turbulence, wind, and temperature. The received signature depends also on further random factors such as the configuration of buildings and terrain and whether the boom is heard outdoors or indoors. For a single flight, the only feature subject to a degree of control is the flight profile and, therefore, the nominal peak overpressure (and other parameters) that may be calculated as characteristic on the average of that flight profile. Human response measured against nominal mean overpressure obtained from community surveys is therefore the most pertinent indicator of public response to the sonic boom at a given boom frequency.

The present data on community response to the sonic boom lack adequate information pertaining to boom frequency and to nighttime sonic boom exposure as well. The data presented in figures I-6 and I-7 provide a guide to acceptability.



## RESEARCH PLANS

### LABORATORY STUDIES

Because of current design trends, it is expected that future configurations of aircraft will generate noises that are closer in level to the background noise in the community and will have noise spectra with relatively more intense low-frequency noise components than do current aircraft. Laboratory studies are planned, with the use of improved facilities, including those of the Langley Aircraft Noise Reduction Laboratory, to study the intrusiveness of aircraft noise, in particular the significance of background noise and the effects of low-frequency noise and noise induced vibrations on the psychophysiological responses of people. By means of flyover noise simulation techniques, tests are being conducted to evaluate proposed retrofit modifications to existing aircraft as well as proposed new configurations and to establish a close correlation between the reactions of people in laboratory simulation situations and real life exposures.

### AIRPORT COMMUNITY NOISE STUDIES

Both short range and long range plans have been developed for airport community noise research. Data will be obtained by means of special tower facilities to define more precisely the propagation losses and the variability of noise propagating through an inhomogenous medium from flight altitudes to the ground at various angles. These data will be correlated with actual ground contour measurements from aircraft in flight in order to improve the capability for predicting contour patterns, particularly at large distances. Long range plans call for repeating community surveys in selected localities in order to evaluate and correlate expected changes in the noise exposures and the associated responses. Preliminary tests are showing that there are positive benefits in retrofit as depicted by subjective rating scales. Unpublished data have shown that a 6 EPNdB retrofit reduction from a base noise level is perceived as less annoying at the 1.1, 2.5, and 3.5 mile measuring points on approach path. Further studies will be conducted with other aircraft, including their various takeoff and landing noise spectra. The aspect of fear is also being studied to determine its role in judgments of aircraft annoyance.

### SONIC BOOM STUDIES

Most of the sonic-boom-related human response studies to date have been focused on the practical operating range of the current generation of supersonic transports for

which the associated sonic boom intensities are in the range 1.5 to 4.0 pounds per square foot. Very little effort to date has been applied to evaluating the responses of people to sonic boom overpressures that may be achievable with the application of new design and construction technologies. Planned research will include studies of a wide range of human responses to sonic boom intensities.

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## II - SOURCE ABATEMENT TECHNOLOGY

### SUBSONIC TRANSPORT AIRCRAFT

The noise we hear and object to today (and for the next decade) is generated by the commercial fleet of subsonic conventional takeoff and landing (CTOL) aircraft. Accordingly, the discussion on CTOL noise in reference to the NASA Quiet Engine and Refan Programs is followed by a discussion of noise associated with supersonic aircraft, short haul powered lift aircraft, and rotorcraft. Much of the work discussed under subsonic aircraft is germane to these other areas of application and will lay a general groundwork with regard to certain common noise contributors; for example, the noise generated by fans and jets and methods of sound absorption. Subsonic aircraft noise will be considered in terms of propulsion system noise and airframe noise. The material covered herein reflects a total NASA posture, including both in-house activities and work done under contract.

### PROPULSION SYSTEM NOISE

The noise due to the engines has been and continues to be the major source of aircraft noise. The sources of noise in a typical turbofan engine are indicated in figure II-1. Noise created by the fan blades and also the compressor blades propagates forward to the cowl inlet and thereafter is radiated to the community. Fan noise also propagates rearward to the fan exit nozzle and is radiated. In addition, the high velocity jet of air from the fan mixes violently with the ambient air and creates noise. Noises from the combustor and turbine propagate rearward to the core nozzle exit and then are radiated to the community. The very high velocity of the core gas jet produces one of the major sources of noise. Other noises (not shown) are radiated outward through the engine and nacelle structure. Finally, noise is created by the fan discharge air flowing at high velocity over the aft surface of the nacelle afterbody. The material to follow considers the various noise sources, what is being done and is planned to reduce the noise generated from these sources, and techniques used to absorb noise which cannot be eliminated at the source. Consideration will also be given to the performance or economic penalties incurred by the measures employed to reduce these noises.

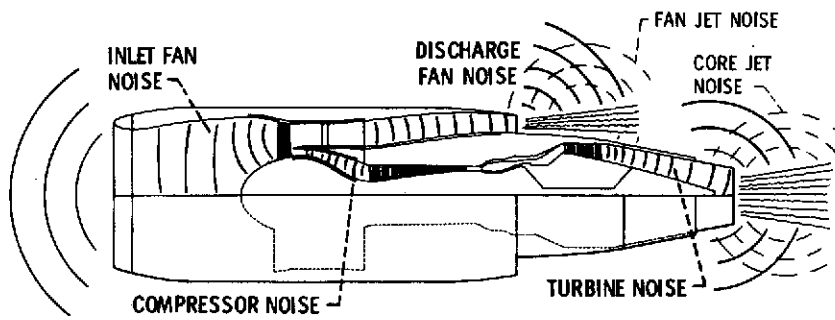
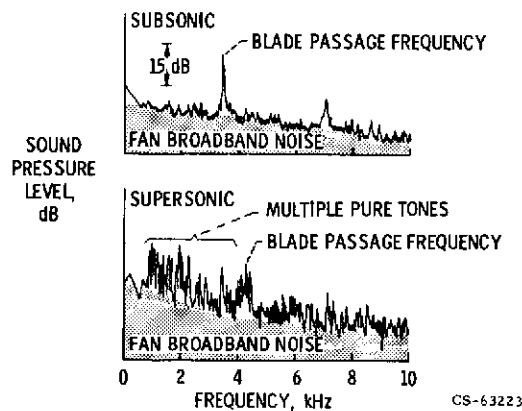


Figure II-1. - Turboprop noise sources.

CS-64045



CS-63223

Figure II-2. - Fan noise spectra at subsonic and supersonic tip speeds.

## Fan Noise

The first and most important function of a fan is to produce pressure rise. Our concern is how to do this noiselessly and without undue penalty. In a fan designed to produce a given pressure rise, there are two parameters that may be traded. These are the fan tip speed and the overall stage loading, conveniently measured by a work coefficient given by the ratio of the average turning of the airstream to the fan tip speed.

Early studies of fan noise indicated that tip speed was highly important in determining the noise. Figure II-2 shows spectra for two fans, one having a subsonic tip speed and one having a supersonic tip speed. Considering first the subsonic tip speed fan, it can be seen that the noise energy appears as discrete tones that are superimposed on a broadband noise. The discrete tones are the cause of the characteristic whine of current aircraft heard on landing. These same noises are seen in the spectra from the supersonic tip speed fan, but a large number of additional discrete tones or spikes are

also evident. These additional tones are associated with the shock waves on the blade leading edges and occur at multiples of the rotational speed of the fan. They may be heard on wide-bodied aircraft at takeoff and are characteristically called buzz-saw or multiple pure tones.

It can be seen from these spectra that tip speed is indeed a factor in fan noise. In fact, two noise regimes exist depending on whether the fan operates at subsonic or supersonic tip speeds.

Several subsonic speed fan stages have been noise tested at NASA along with one supersonic tip speed fan. The data from these fans provide a good indication of the state-of-the-art in fan noise. It is necessary to consider the aerodynamic and noise features of these fans as these features qualify the data.

First, it should be noted that the fans were all 6 feet (ft) in diameter. This means that no scaling of the data is required. They are all designed without inlet guide vanes since the extra blade row was a potential noise source. Rotor-stator axial spacing was at least two rotor blade chords to allow rotor wakes to decay before impinging upon the stators. While this wide spacing reduces noise about 3 decibels (dB), it also serves to add length and weight to an engine. There also is some indication that this spacing costs about 1 percent in fan stage efficiency. Finally, the ratio of stator vane to rotor blade number was selected on most of the fan stages so that blade-passage frequency tones were cut off (do not propagate to the far field) according to the Tyler-Sofrin theory (ref. 1). Cutoff requires that the vane blade ratio be about 2. This requirement leads to thin, narrow stator vanes that create structural problems and affect aerodynamic performance. In one case, stall margin was reduced from 16 to 7 percent by meeting the cutoff vane number requirement. The aerodynamic design of the fan stages were state-of-the-art. Specific flow rates were generally about 41 pounds per square foot per second ( $\text{lb}/(\text{ft}^2)(\text{sec})$ ). Local values of the diffusion factor were not allowed to exceed about 0.5.

Figure II-3 shows the matrix of fans tested in terms of the overall performance parameters. Fan stage pressure rise is plotted against tip speed with the average work coefficient shown as a parameter. It can be seen that a range of pressure ratios (work coefficient) is covered at constant tip speed and that a range of tip speeds (work coefficient) is covered at constant pressure ratio. Several of the fans also lie close to a line of constant work coefficient.

Figure II-4 shows the maximum perceived noise level along a 1000-ft sideline as a function of fan pressure rise. These data have been normalized to unit thrust. The correlation for subsonic tip speed fans shows a total spread of about  $\pm 2.5$  perceived noise decibels (PNdB). This correlation shows that perceived noise increases by 3 PNdB for each doubling of the thrust and by 4.2 PNdB for each doubling of fan pressure rise. An equivalent functional dependence can be obtained in terms of fan diameter and tip speed. In these terms, the noise increases by 15 PNdB for each doubling of tip

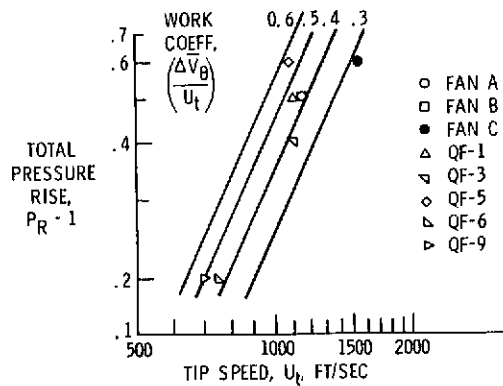


Figure II-3. - Fan design parameters.

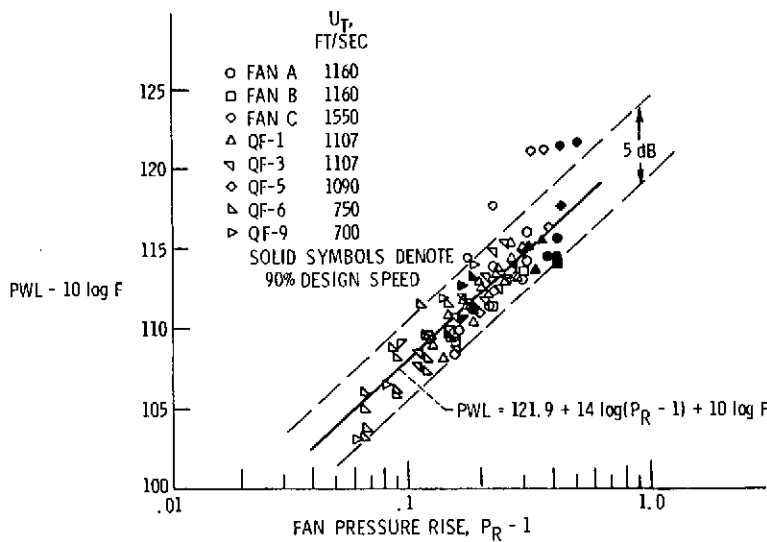


Figure II-4. - Correlation of perceived noise from low tip speed fans. Maximum value, 1000 ft sideline.

speed and 6 PNdB for each doubling of diameter. These fans, designed for low noise, have demonstrated the lowest noise levels known.

As fan tip speed moves into the supersonic range, a new noise source emerges. As noted earlier, this source is associated with the shocks on blade leading edges. Because of the blade-to-blade manufacturing differences and localized flow differences, the shocks are not identical with the result that some overtake and merge with others. This leads to the multiple-pure-tone signature observed in the far field.

Current fan design procedures require supersonic tip speeds for single-stage fans at fan pressure ratios above about 1.6, and they may be employed at pressure ratios as low as 1.4. The upper limit on pressure ratio with current design techniques is thought

to be about 1.9. At larger pressure ratios, multistage fans are required. This stage addition allows a reduction in tip speed relative to that required for a single-stage fan at the same pressure ratio. The result is that the reduced tip speed may offset the noise increase caused by the addition of a second stage. There are no data available on low-noise, two-stage fans to permit this comparison. In fact, an objective of the future program is to obtain the comparison. The two-stage fan data shown were obtained from older fans, such as those on the JT3D and JT8D engines. Figure II-5 includes perceived noise from one-stage supersonic tip speed and two-stage fans as functions of fan pressure ratio. The data are at the maximum 1000-ft sideline and for a 90 000-lb thrust. For completeness, the subsonic-tip-speed data in figure II-4 are also shown at the fan tip speed corresponding to takeoff operation.

The noise increment in passing from single-stage, low-tip-speed fans to single-stage, high-tip-speed fans is reasonably well documented. One fortunate circumstance is that the multiple-pure-tone noise causing the high-tip-speed-fan-noise increment is very amenable to suppression by acoustic treatment. A relatively small amount of treatment is effective. The noise level increment incurred with two-stage fans is derived from data for fans with few or no noise reduction features in their design. Studies indicate that these levels may in fact be no more than for the high-tip-speed, single-stage fans. Future work is intended to resolve this point.

Figure II-5 shows that for a 90 000-lb thrust a variety of fans can be selected to produce noise levels at a 1000-ft flyover in the 100 to 120 PNdB range. Selection of a particular fan depends on the fan configuration, for example, stage number, tip speed, and the design pressure ratio, required. The mission to be performed will exert a large influence on the fan selected.

In the Quiet Engine Program, NASA has examined several techniques for reducing fan noise. These have included rotor leading edge serrations, casing boundary layer

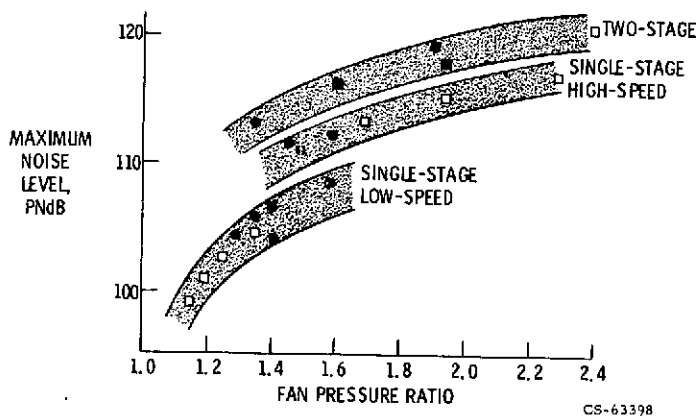


Figure II-5. - Fan noise levels. Thrust, 9000 lb; 1000 ft flyover.



bleed, and leaned stators. Of these, only leaned stators have thus far shown any significant overall noise reduction. Even here the reduction was only of the order of 2 dB. However, leaning the stators did result in one to two points of improvement in fan efficiency, and this is of interest. All of these techniques and others need to be further explored in detail to determine designs that will yield maximum noise benefits.

Future efforts are in this vein. Industry and university responses are anticipated currently on basic research efforts being solicited in several noise problem areas including fan noise. Additionally, a contracted effort is anticipated shortly on new and novel techniques for fan source noise reduction.

## Jet Noise

Jet noise can be one of the major contributors to the total noise generated by subsonic CTOL aircraft operating near airports. The level of jet noise is primarily determined by the jet exhaust velocity (fig. II-6). Consequently, the high exhaust velocities of the older CTOL aircraft and SST engines make it difficult for those engines to meet current FAR-36 standards. On the other hand, advanced CTOL engines have lower exhaust velocities so that the noise goals can be more readily met so far as jet noise is concerned.

It should also be mentioned at this point that the forward speed of the aircraft lowers the jet velocity relative to the airstream and therefore reduces the noise level. Some effects of forward speed on noise generation are shown in figure II-7, which compares the noise spectrum from a 2-inch (in.) circular nozzle with an airspeed of 100 knots (KTS) to the case for no forward speed. Forward speed was simulated by placing the 2-in. nozzle in a large free jet (ref. 2). A forward speed comparable to takeoff (100 KTS) clearly reduces the high frequency jet noise generation. Experiments on the effect of forward speed are continuing at NASA and elsewhere.

In addition to the level of the noise the frequency of the noise is important. Noise near a frequency of 3000 hertz (Hz) sounds loudest to the human ear. It sounds decreasingly loud at lower and higher frequencies. Therefore, noise annoyance is primarily reduced by reducing the noise level; but it can also be reduced by keeping the frequency of the noise far away from frequencies having high annoyance weighting.

The general methods of reducing subsonic jet noise level when necessary are:

- (1) Reduce the noise generated
- (2) Redirect the noise already generated away from the community
- (3) Absorb the noise already generated

The specific problem areas and the progress made in understanding subsonic jet noise, and in particular its suppression, are now discussed.

Figure II-8 contains sketches of common nozzle shapes used on engines, namely the

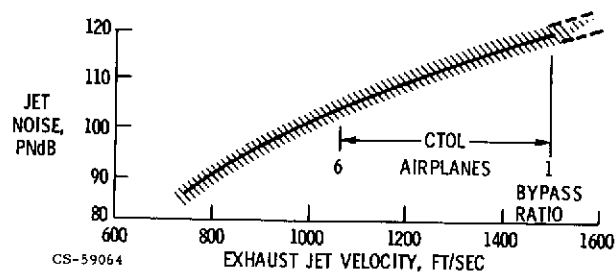


Figure II-6. - Effect of engine exhaust velocity on jet noise for a 500 ft flyover. Airplane gross weight, 100 000 lb. Total thrust (4-engines), 60 000 lb.

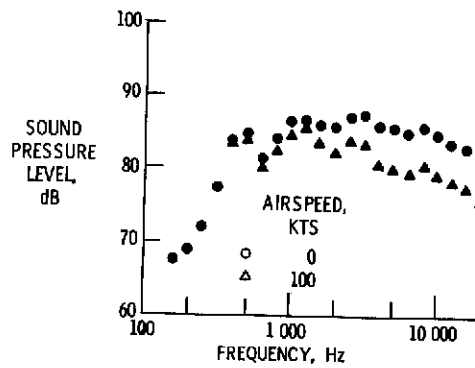


Figure II-7. - Effect of airspeed on noise spectra of a model, 2 in. diameter convergent nozzle. Exhaust velocity, 835 ft/sec. Angle from inlet,  $100^\circ$ .

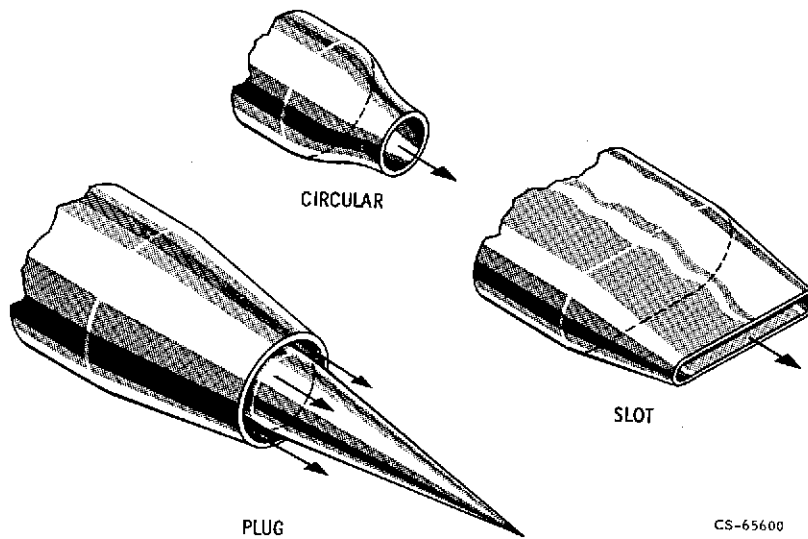


Figure II-8. - Common types of nozzles.

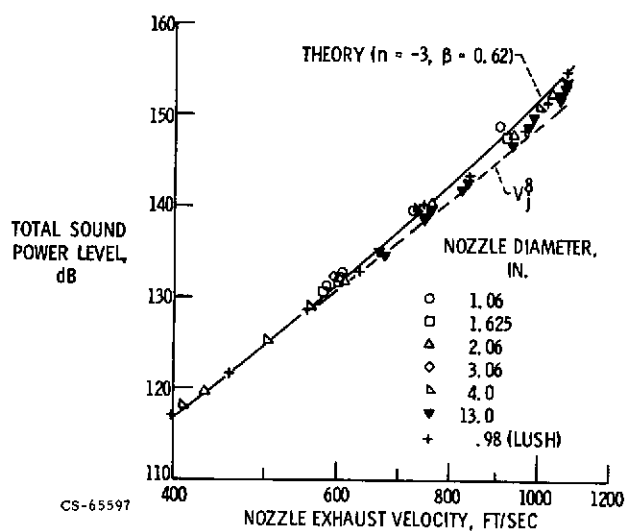


Figure II-9. - Comparison of jet noise power for circular, slot and plug nozzles. (All data scaled to an area of 1 ft<sup>2</sup> and 77° F.)

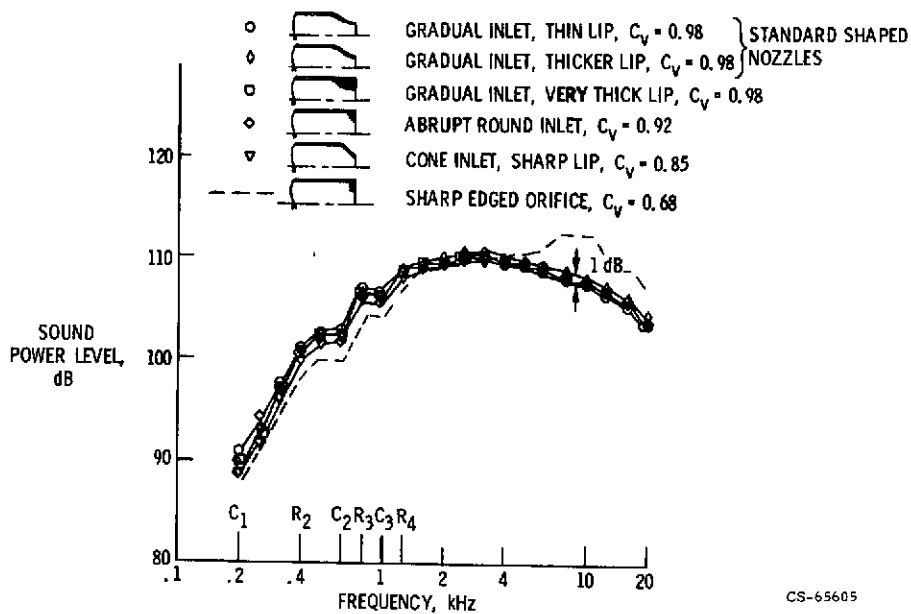


Figure II-10. - Effect of nozzle inlet and lip shape on noise. Nozzle exhaust velocity, 785 ft/sec; diam, 15/8 in.

circular, slot, and plug nozzles. The first question to be answered is whether any of these generate less noise. This is answered in figure II-9. Typical data for the total noise power generated by each of these nozzle shapes are plotted as functions of the jet exhaust velocity. Only a very small sample of the large amount of subsonic ambient temperature jet noise data, taken at the NASA Lewis Research Center and elsewhere, has been plotted here. The equivalent area diameter of the nozzles ranged from about 1 in. to 1 ft; therefore, the data have been normalized to a common area of 1 ft<sup>2</sup>. It is clear from this figure that the total noise power generated at a given subsonic velocity by slot and plug nozzles is the same as that generated by circular nozzles of the same area. A circular nozzle typically has somewhat better aerodynamic performance. Thus, it is doubtful that a reduction in jet noise generation can be achieved by using either slot or plug nozzles.

The nozzles described in figure II-8 are of good aerodynamic design in that they have a gradual area contraction and a thin lip. To aid our understanding of jet noise it was helpful to see what effect a thick lip and a nongradual inlet would have on the jet noise generation (ref. 3). Figure II-10 contains plots of the noise power spectra for a number of circular nozzles of the same diameter at the same peak or isentropic jet velocity. The data are for nozzles that differ only in their inlet shape and lip thickness. Except for the sharp edged orifice all generate the same noise. This similarity also occurs for the noise radiation patterns and at higher and lower subsonic velocities than plotted in figure II-10. This conclusion can probably be carried over to slot and plug nozzles.

Although the example nozzles of figure II-8 show little difference in noise generation characteristics, there are some other nozzle types that appear to generate less noise. For instance, multitube nozzles are known to be useful for noise reduction. Evaluations of such nozzles have been accomplished on an ad hoc basis and verifications and improvements have been made by parametric variations. It has been shown that multitube suppressors shift the frequency of the spectrum peak upward compared to that of the basic nozzle as shown in figure II-11. This frequency shift is beneficial because of the associated increase in atmospheric propagation losses and the relatively higher attenuation provided by sound insulating structures. There is also the potential for optimizing the spectra for subjective reaction purposes. The mechanisms of noise suppression are still not well understood; however, it is found that the noise sources are concentrated closer to the multielement nozzle exit than for an equivalent single element nozzle exit. This suggests that lined ejectors will probably be more effective in reducing noise for the multitube nozzles than for the standard nozzle.

Another suppressor nozzle is the coannular nozzle. Coannular nozzles are quieter than two separate jets having the same total throat area. The noise level is dependent on the fan to core area ratio and on the fan to core velocity ratio. Nozzles with large fan to core area ratios are quieter. The coannular nozzle is quietest when the fan to

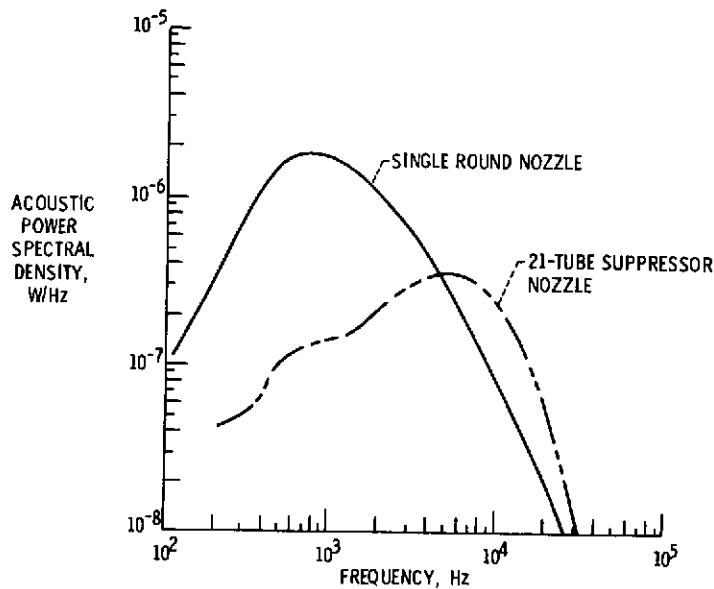


Figure II-11. - Effects of nozzle geometry on radiated acoustic power of constant flow momentum and constant area. Area, 4.52 in.<sup>2</sup>; jet velocity, 694 ft/sec.

core velocity ratio is about 0.5. Unfortunately it is usually not practical to use an engine cycle with such a low velocity ratio (0.7 to 0.9 is more common).

Another method of alleviating jet noise is to redirect some of the energy away from the observer on the ground. This can be accomplished by means of ejector shields, by rigid surface shielding such as that provided by a wing (ref. 4), and by means of reflections due to impedance discontinuities in the flow.

Experimental and theoretical work is presently being conducted relative to the redirection of jet noise, and all three of the previous approaches are being studied. Particular attention is being given to experimental evaluation of reflections caused by a sound gradient interface between the jet and the observation points. Laboratory experiments using helium to simulate an impedance discontinuity in a jet have produced high transmission losses over a broad range of frequencies. Satisfactory results have been obtained using both point sources and a model scale jet. Experiments which have produced useful noise reductions due to wing shielding of the noise from top-of-the-wing mounted jet exhausts for both subsonic and supersonic jet flow velocities are continuing in scale model studies.

The third method to reduce the jet noise is to absorb some of the generated noise. This can be done by exploiting the absorption of high frequency noise by the atmosphere and by employing acoustic linings. For example, the previously mentioned ejector shield can be lined with sound absorbing material. Furthermore, attempts can be made to bend the sound rays (by velocity or temperature gradients) toward sound absorbing

material or so that they take a long path through the atmosphere to increase the noise reduction.

In summary, subsonic jet noise can be reduced by employing high bypass ratio engines with low engine exhaust velocities. With existing engines the jet noise can be reduced somewhat by techniques which reduce the generation of noise and/or redirect and absorb it.

NASA is currently conducting in-house research to develop better methods and techniques of suppressing low velocity jet noise.

### Other Noise Sources

Fan and jet noises have now been reduced in research engines to the point that other noise sources, such as turbine and combustor noise, become evident. In fact, with quiet engine A, a 6300-Hz turbine tone stands out of the overall noise spectrum when the engine is operating in the fully suppressed nacelle. The turbine tone contributes measurably to the perceived noise at the rear of the engine. These noise sources are now starting to be investigated in a systematic manner. The discussion to follow is based primarily on what has been gleaned from analysis of complete engine data.

Both discrete tone and broadband noise emissions have been observed originating within the engine core. The discrete tones originate with the rotating machinery, and broadband noise can also be generated. In addition, broadband noise can be generated by combustion processes and by obstructions and discontinuities in the flow path.

The existence of these other noise sources has been demonstrated with data of the kind shown in figure II-12, which shows how engine noise changes with jet velocity. For many years it was widely held that all the noise measured was jet noise, and that at low velocities the noise changed only slightly with changes in velocity, while at higher velocities the change in noise was greater. Recent work at NASA has shown that, except for very high speed jets, jet noise per se follows an eighth power relationship at all speeds, which is consistent with theoretical arguments. The higher than predicted noise at low velocities, which has been reported as jet noise by many investigators, is in fact of core-engine origin and reflects a faulty interpretation of the experimental data. More detailed spectral analyses of such data confirm these findings.

A typical engine sound spectrum appears as figure II-13. It is usually dominated by fan machinery and core jet noise as illustrated; but, other spectral components, tones in particular, can be shown to exist and are identified with the blades of the turbine. For engines where the fan and jet noises have been reduced, these turbine-associated noises play a significant role in annoyance such that full potential of further reductions of fan and jet noises cannot be realized unless the turbine noise is also reduced.

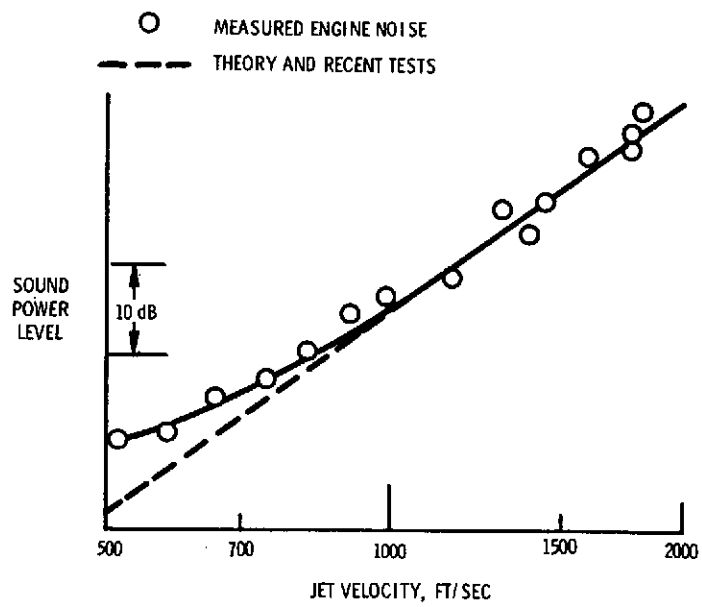


Figure II-12. - Jet noise.

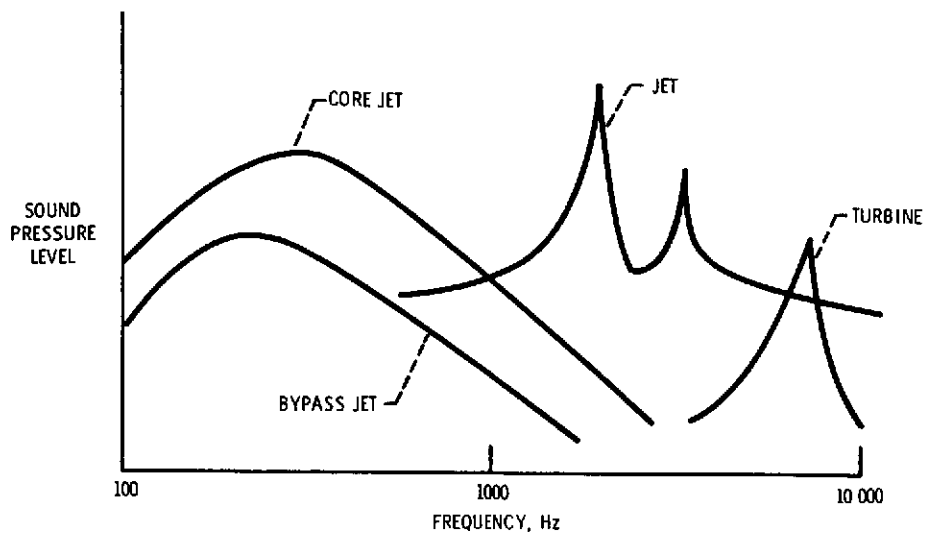


Figure II-13. - Spectral components.

If this turbine noise has been correctly identified, two techniques used to reduce fan noise may be applicable in reducing turbine noise. The first involves reducing the tones by spacing out the adjacent blade rows in the turbine by mechanical design. The second method employs the application of sound absorbing materials, or core suppressors, to the engine. Wide spacing of turbine blade rows is costly to demonstrate and involves significant engine weight penalties in actual use. One experiment run under contract for FAA has demonstrated that significant turbine noise reductions are possible by wide spacing in a single-stage turbine (ref. 5) but also that the turbine efficiency was reduced significantly.

Some experiments have been conducted using sound absorption materials. Figure II-14 shows the results of applying core suppression materials on a JT3D engine at approach power. An effective reduction of turbine noise is shown. A similar experiment was performed with quiet engine C. These data are shown in figure II-15 again demonstrating the potential of core suppression.

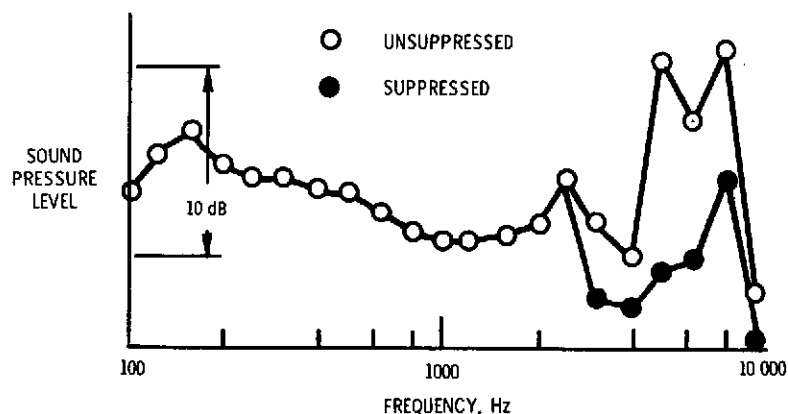


Figure II-14. - JT3D turbine noise suppression.

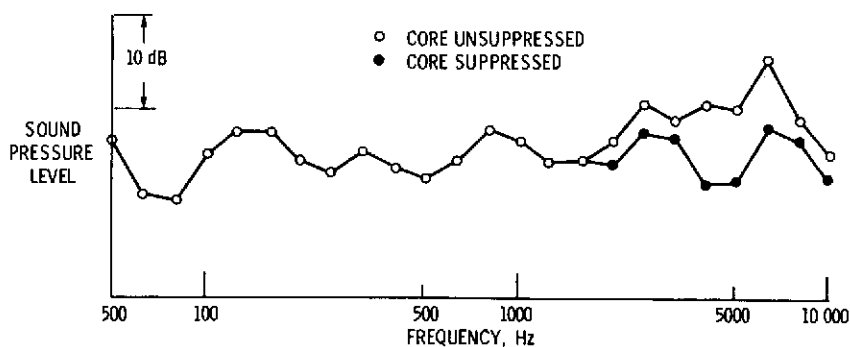


Figure II-15. - Quiet engine C sound spectra.



These preliminary results, though encouraging, address only one of many other potential sources. Knowledge of the core noise problem is far from adequate. The data of figure II-16 are presented as an example. This shows the effect of the addition of a nacelle suppressor and a core suppressor to quiet engine A. Significant high frequency noise reductions are observed, but there remains a haystack in the spectrum whose origin remains unclear. Other such anomalous spectral components have been variously observed and remain to be explained. More can be expected to be discovered as testing progresses with the NASA quiet engines, but such tests offer the potential of identifying and resolving many of these problems also. Tests are planned for quiet engine C, for example, using a carefully designed core suppressor to pursue further the core noise problem.

The second noise associated with the core engine occurs at low exhaust velocities, influences the low frequency portion of the spectra, and is associated with internal conditions in the engine. The fact that internal conditions can affect the low frequency noise has been demonstrated in several recent tests. Figure II-17 (from ref. 6) shows the behavior of observed noise as a function of jet velocity for various internal flow conditions. It shows noise levels which are controlled by the low frequency part of the spectrum. Curve C was obtained from nozzle experiments in which considerable effort was expended to eliminate upstream turbulence and flow noise. Curve B comes from tests of a simulated engine where the combustor cans were removed from the upstream piping. Curve A represents data from a variety of engine and model rig tests. It is apparent that internal flow conditions have an effect on far field, low frequency noise.

Few tests have been performed to examine the effect of internal acoustic suppression treatment on low frequency noise; however, test results from the NASA quiet fan (ref. 7) have shown that significant reductions of low frequency noise do occur as a result of internal acoustic suppression. This result was accomplished by the broadbanded nature of the suppressor in spite of the fact that it was designed for attenuation of high frequency noise.

A test to examine the effect of acoustic suppressors designed for low frequency attenuation was performed on a J65 turbojet engine (ref. 8). The results of the test are shown in figure II-18. A significant reduction of the low frequency noise is seen in the figure.

These experiences show that a portion of the low frequency noise, which has in the past been called jet noise, can be reduced or eliminated by appropriate internal modifications. Some modifications which have been effective are streamlining flow passages and struts, as well as placing acoustic suppressors in the ducts for the purpose of attenuating low frequency noise.

A source of low frequency "core noise," which can become important when the engines are operated at part throttle conditions during approach to an airport, is the noise generated in the combustor section of the engines.

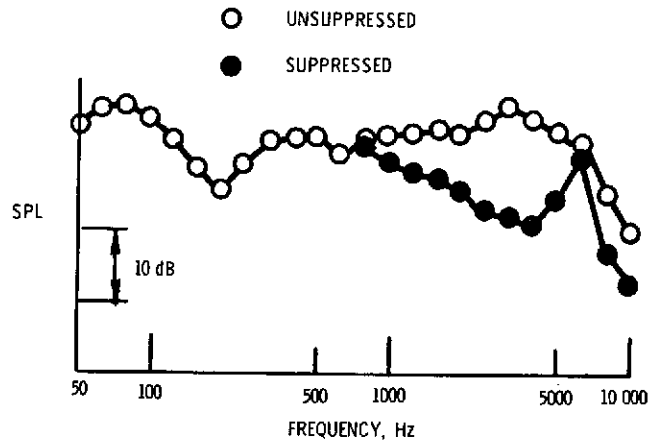


Figure II-16. - Quiet engine A sound spectra.

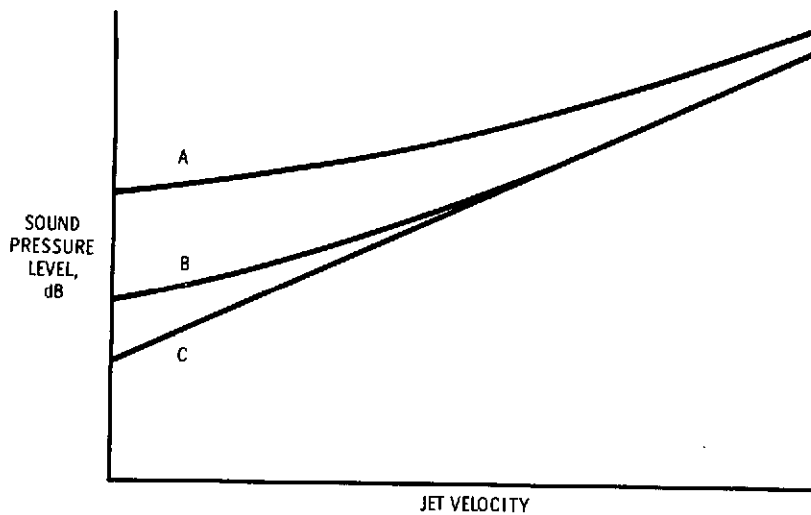


Figure II-17. - Low frequency noise as function of jet velocity (ref. 6).

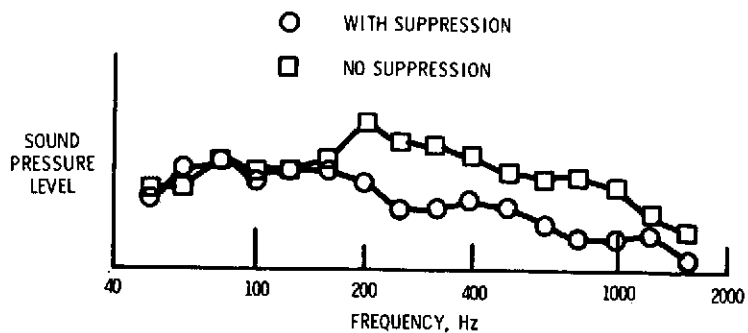


Figure II-18. - Spectra of noise showing effect of suppression on J65 engine (ref. 8).

Recent tests reported by Boeing in reference 9 show that burners (whether or not they are lit) contribute to the noise field. Typical Boeing data are given in figure II-19 for a large burner, a small burner, and no burner in the jet supply duct. The noise spectra at 25 ft from the exhaust nozzle is given with the flame off in II-19(a) and with the burners lit in II-19(b). The presence of the burner in the duct generates pressure drop (or turbulent eddy) noise even with no flame - especially for the high resistance small burner. With the burners lit there is a large increase in low frequency noise

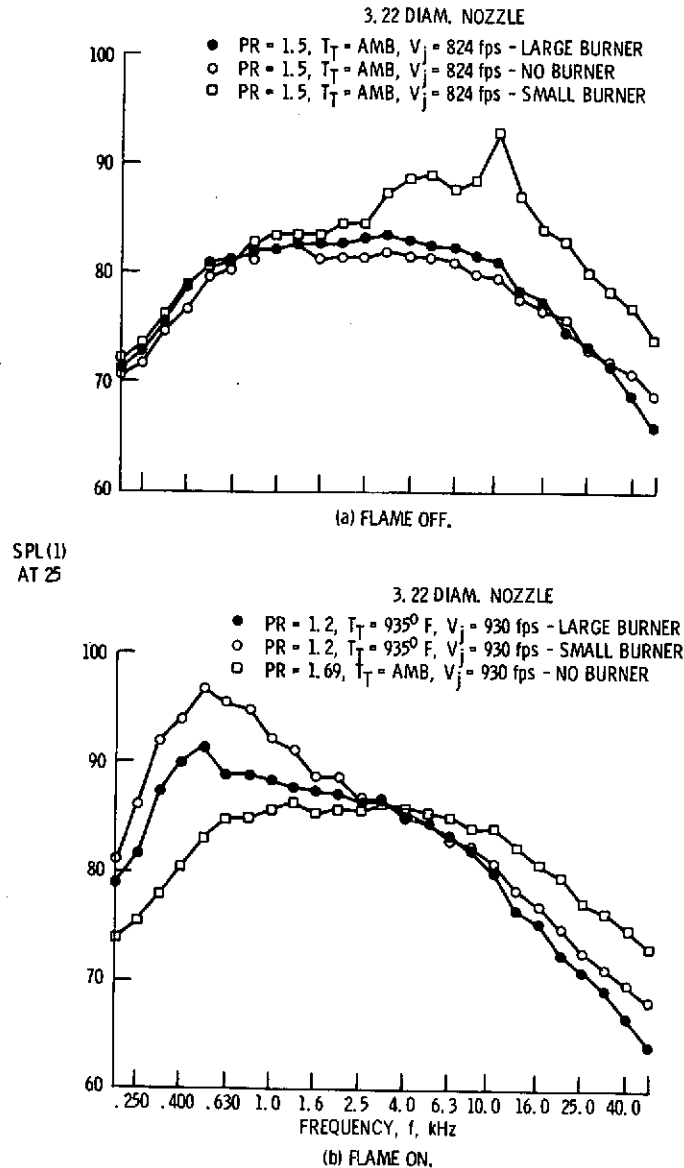


Figure II-19. - Burner noise.

caused by the presence of the flame accompanied by some reduction of high frequency noise.

NASA is initiating plans to conduct in-house combustor noise tests using existing facilities in order to determine means for predicting core noise levels and to find viable means of reducing the core noise floor. In addition, consideration is being given to an evaluation of industry experience in this area of jet noise and a compiling of available acoustic data. A current contract with Princeton University is also providing insight into the basic principles and problems underlying combustion noise (ref. 6). Noise generation by a subsonic flow discharging from a combustion chamber was examined with regard to the relative importance of combustion as a source of noise in such a flow system. Measurements of pressure fluctuations inside the combustor were compared with far field noise measurements by direct cross correlations. The cross correlations and derived cross-spectral densities verify that much of the noise originates inside the combustor. A first-order fluid mechanic perturbation model is used to predict exit plane velocity fluctuations due to internal pressure fluctuations. This unsteadiness at the exit plane is assumed to behave as an acoustic monopole which radiates to the far field. Far field noise levels estimated on this basis are in good agreement with measured values. The overall noise level from the combustor jet is found to be 10 to 20 dB higher than for an equivalent clean, cold jet at the same exit velocity.

As was mentioned earlier, several engines, such as quiet engine A, have been suppressed to the point that core engine noise, particularly turbine noise and low frequency noise associated with the various internal obstructions (combustors, struts, etc.), are limiting or determining the far field noise. Research and technology studies in these areas are only getting started. It is evident that cleaning the internal flow passages and the use of core suppressors can be effective in reducing these noises. In thinking of the penalties associated with the reduction of these noises, it seems that core suppressors should not entail large penalties because they are involved with about 20 percent of the flow. In fact, cleaning the flow passages should decrease losses and perhaps compensate for the suppressor.

Thrust reversing is used to shorten the landing distance for both conventional and short-haul powered-lift aircraft. In addition, augmentor-wing STOL airplanes may use core-jet reversal to steepen the approach flight path. In the interests of minimizing the noise associated with aircraft operations, all potential noise sources should be considered. Until recently, thrust reverser noise has received little attention.

NASA has initiated studies of thrust reverser noise (ref. 11). Target-type reversers were used in the earliest tests because of their simplicity and because they can reverse both circular nozzle (refs. 12 and II-20) and slot nozzle flows. Shown in figure II-20 are two reverser types that have been tested, namely, a V-gutter target and a semicylindrical target.

The noise directivity of a semicylindrical reverser is shown in figure II-21 as a

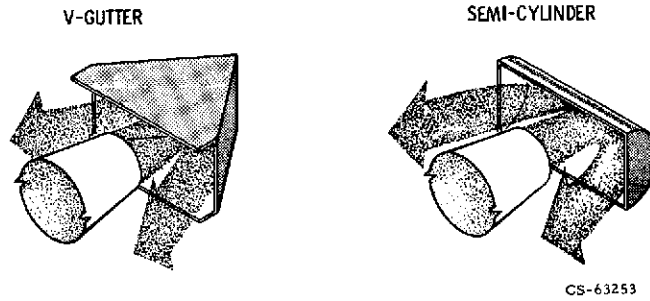


Figure II-20. - Target-type thrust reversers.

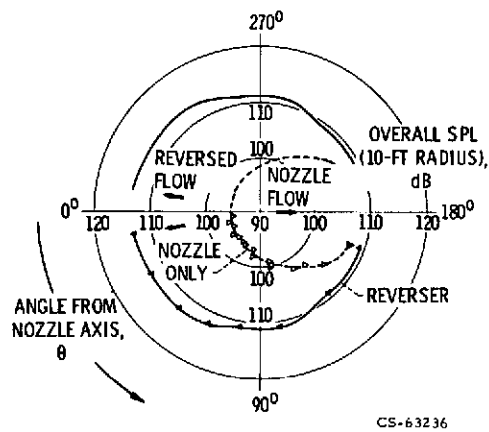


Figure II-21. - Thrust reversal noise directivity.  
Nozzle, 2 in.; jet velocity, 960 ft/sec; cylindrical reverser.

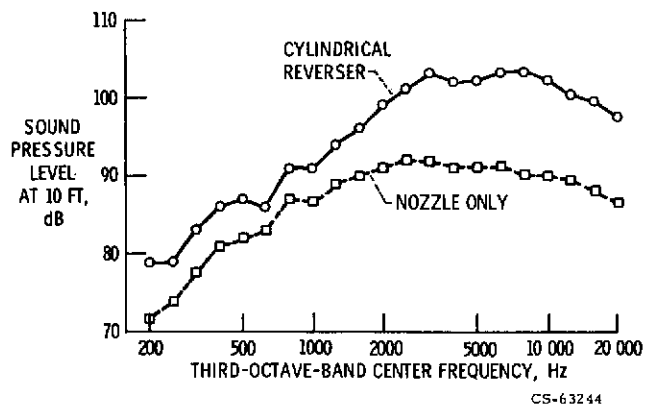


Figure II-22. - SPL spectra for reverser and nozzle at angle of maximum sideline noise.

polar plot of the overall sound pressure level (OASPL) as a function of the angular position. The jet noise from the 2-in. circular nozzle alone has a pronounced directivity. The maximum OASPL is 107 dB (re 20 N/m<sup>2</sup>) at an angle of 160°. The minimum, toward the upstream direction, is 12 dB less than the maximum. The reverser noise, in contrast, is nearly uniform in all directions and is everywhere louder than the bare jet maximum by 1 to 6 dB. Toward the upstream direction, the noise level for the reverser is about 17 dB greater.

Maximum sideline noise spectra for the nozzle and reversed jets are shown in figure II-22. The sound pressure levels (SPL) for the cylindrical reverser exceed those for the nozzle over a broad frequency range, and its spectrum peaks at frequencies higher than those of the bare nozzle. This peaking at higher frequencies increases the perceived noise level, but the higher frequencies attenuate more rapidly in the atmosphere than the lower frequency nozzle noise. Therefore, at short distances from the aircraft, such as the 500-ft sideline often used in defining STOL noise objectives, thrust reversal may well be a dominant noise source, while at distances appropriate for CTOL aircraft certification, atmospheric attenuation may reduce the reverser noise problem somewhat.

From the preceding information, it is obvious that thrust reversers can generate more noise than nozzles, at higher frequencies, and direct the noise more strongly toward the critical sideline and flyover points. To present this problem in more specific terms, recent preliminary data on cascade reversers have been scaled up to the case of a CTOL aircraft of 300 000 lb gross weight using fan jet reversers on four NASA quiet engines. Figure II-23 shows the perceived noise level (PNL) distribution along the 0.35-nautical-mile (n. mi.) sideline, not including extra ground attenuation. The maximum PNL is 95 PNdB or less, which would be no problem with current regulations, but it

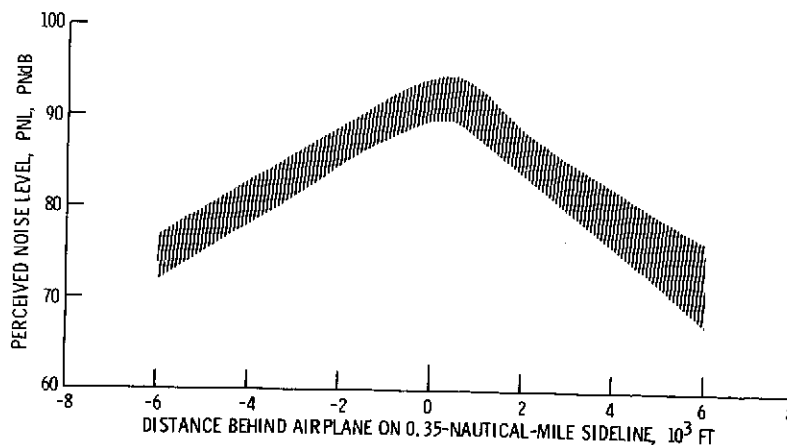


Figure II-23. - Thrust reversal noise on 0.35-nautical-mile sideline for 300 000-lb CTOL airplane with four NASA "Quiet Engines"; cascade type reversers.

could become a marginal problem for compliance with FAR-36 minus 10 PNdB, and it certainly would be problem for FAR-36 minus 20 PNdB. Similar calculations have been made for a 100 000-lb gross-weight augmentor-wing-type STOL aircraft. For in-flight core-jet reversal (refs. 12 and 13) and for wing-slot reversal on the ground, the PNL's were well above the 95-PNdB design goal at 500 ft. This illustrates the point made in the preceding paragraph that thrust reverser noise is more of a problem at short distances.

Since thrust reversal noise can be a significant problem, especially for STOL aircraft and for decreased certification noise levels, methods of reducing reverser noise are being studied. Perhaps the use of acoustically treated doors or shields might be used to reduce reverser noise on the sideline. Preliminary experiments with a target reverser have indicated possible shielding benefits.

### Suppression of Internal Engine Noise

In spite of the source noise reductions which have been achieved in recent years, acoustic suppressors are required in addition to meet the low noise goals of today. Even more noise suppression must be achieved so that the anticipated lower noise goals of the future can be realized. To be effective, the noise suppressors must be located along the propagation path between the noise source and the observer. This limits the use of suppressors to quieting the internal noise sources of the engine. The suppressors are located in the ducts emanating from these noise sources as shown in figure II-24.

Two types of noise suppressors have been studied in the past few years which can be used to reduce the noise of aircraft engines. The first, which has been the most extensively investigated, is the dissipative acoustic liner. In this type of liner, the acoustic

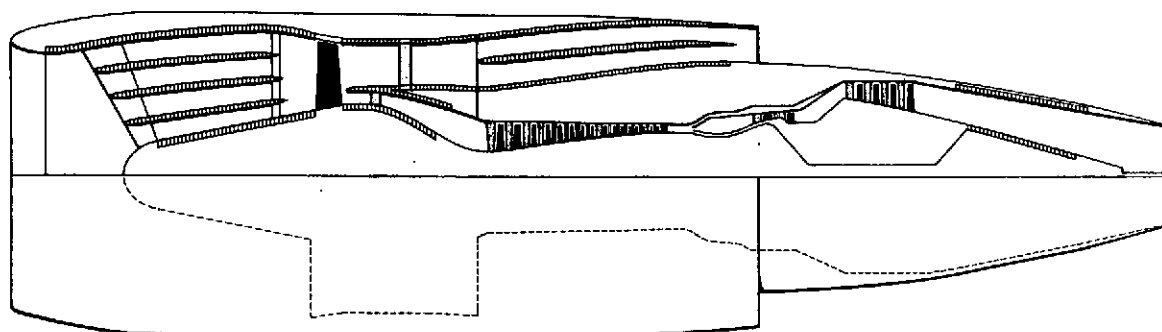


Figure II-24. - Engine with suppression.

energy is directed into an absorptive material on the walls where it is dissipated within the wall material. The dissipation occurs due to shearing of the flow in very small passages or through loss of energy of the jets formed by oscillating flow through the small holes in the wall.

The second type of suppressor, the sonic (or choked) inlet, is essentially a reflective type of device. The simplest explanation of its operation is that if the steady flow within a duct has obtained sonic velocity then a sound wave cannot propagate against this flow. This implies that this principle can be applied only when the sound is propagating against the steady flow. In an actual inlet, however, the mechanism is much more complicated than that implied previously. There will be continuous reflections of the sound wave caused by the varying duct diameter and steady flow Mach number. Radial and transverse velocity gradients also exist which will refract the sound waves away from the axial direction where they can be swept back away from the inlet by the steady flow. Experimental data indicate a steady increase in suppression as the average inlet Mach number approaches one.

A collaborative NASA/General Electric Company parametric study on choked inlets is underway. The work involves both acoustic and aerodynamic measurements of a family of 19 different inlet configurations which should provide significant inlet quadrant noise suppression. The tests are being accomplished on a 12-in. -diameter fan, and the hardware represents elements of variable geometry cowl and centerbody systems. Particular attention is being given to measurements of inlet flow profiles in order to make direct correlations with both the internal and external inlet noise fields.

Both types of suppressors have been tested and have demonstrated that very large noise attenuations can be obtained. Each, however, has its own unique problems which must be solved before they can be considered as truly efficient suppressors. The dissipative suppressors at present require splitter rings for the large attenuations that are anticipated in the future. These rings add to the nacelle weight and to the wetted area which increases the total pressure losses. These losses will be discussed in more detail later. The choked inlet requires small diffusion angles in order to keep the total pressure losses down to an acceptable level. This requires very long inlets, especially for CTOL engines where wide changes in inlet flow occur between takeoff and approach. There is also a major problem of the variable geometry, actuation devices, and sliding seals which add to the complexity and weight of the system and compound the control problem.

With continued research, the problems will probably be solved so that both types of suppressors can be used in a more efficient manner. The dissipative suppressors could be used today to obtain large noise attenuations if the performance and weight penalties can be accommodated.

One of the problems in interpreting noise suppressor results from experimental data is illustrated in figure II-25. When a fan noise suppressor is designed for large



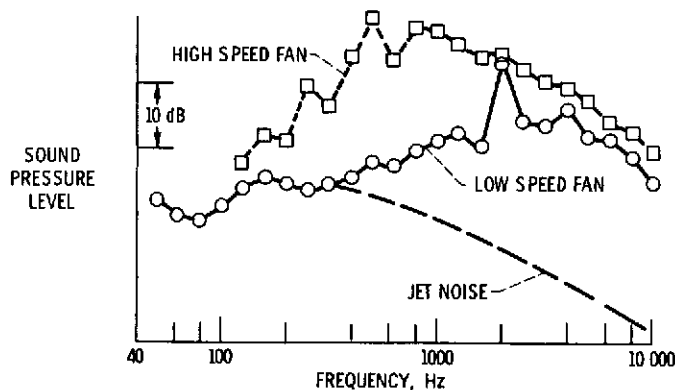


Figure II-25. - Noise spectrum requiring suppression - low speed fan.

attenuations, the fan noise radiated to the far field can be made to be less than some other noise floor such as the jet noise. The jet noise floor is shown here only as an example. Other sources may include cowl scrubbing noise, turbine noise, combustion noise, casing radiation, or even mechanical accessory noises. In the case of fan component tests, the installation noise such as the driving device (motor or turbine) may present a noise floor.

Because of these noise floors, there has probably never been a test of a complete engine with large amounts of acoustic suppression in which the total magnitude of the suppression could be evaluated. An example of this point can be found in the results from the NASA Lewis quiet engine tests to be discussed later. The suppressors for this engine were designed to produce about a 15-PNdB noise reduction. It was anticipated in advance that these decreases could never be reflected in corresponding overall engine noise levels, but the suppressors were designed so that this large suppression could possibly be observed on a fan component test. However, a 7-PNdB noise reduction was observed with the engine test. At takeoff, the jet noise limited the noise reduction measured, and at approach, the turbine noise was limiting. In view of the previous discussion, the total suppression effectiveness with regard to a single source cannot usually be determined from tests with a complete engine.

An example of the large attenuations which have been observed with dissipative liners is shown in figure II-26. This is inlet data at  $50^\circ$  from the inlet axis which is less subject to contamination by noise floors than the aft data. Even in this inlet case, however, the suppressed noise data are clearly limited by the jet noise floor up to at least 1000 Hz, and the high speed, quiet engine C data show a turbine noise floor around 8000 Hz.

An example of much larger noise suppression of a high-bypass engine is the TF-34 turbofan engine tests. The acoustic treatment for these engine tests was designed by NASA Lewis and General Electric. The highly suppressed engine is shown in figure

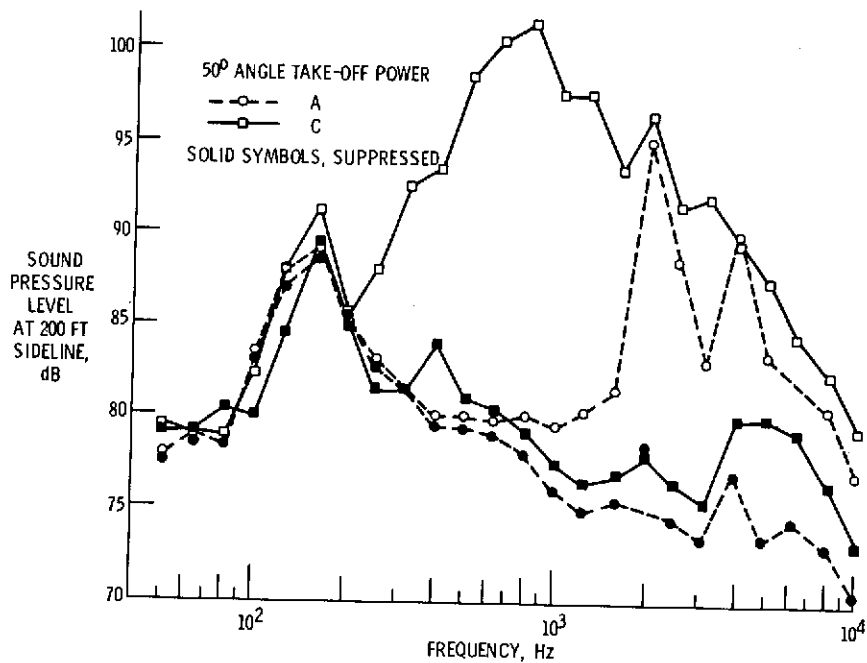


Figure II-26. - Comparison of engine inlet spectra.

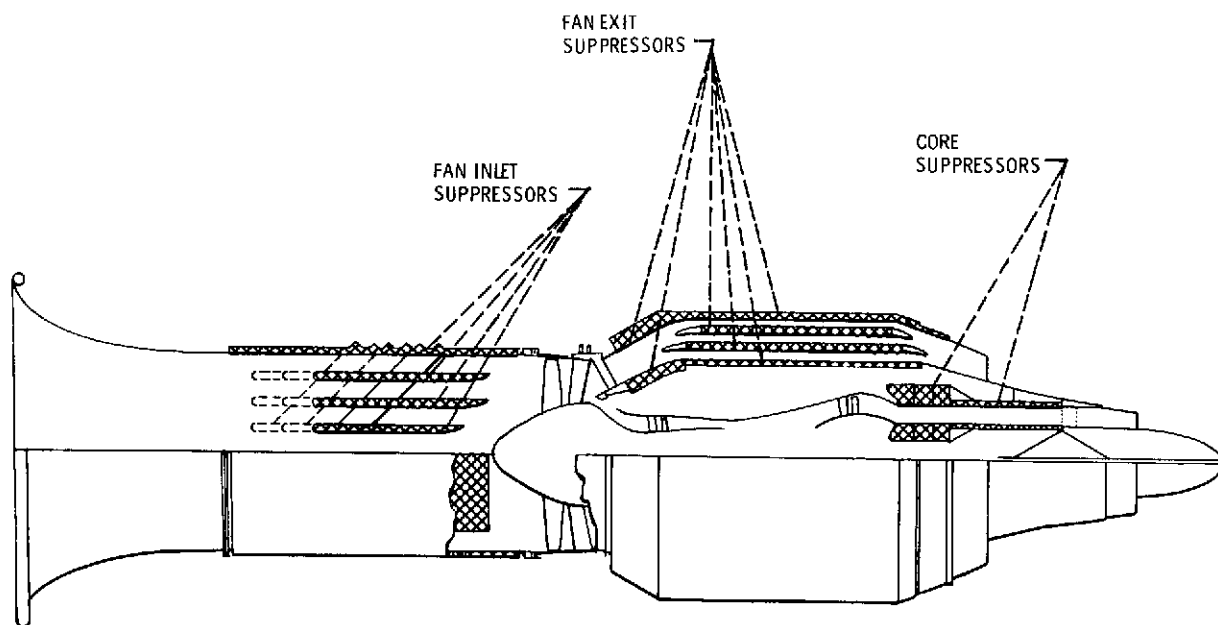


Figure II-27. - TF34 fully treated nacelle separate flow.

II-27. The design incorporated three treated splitter rings and treated outer duct wall at the fan inlet. The aft fan treatment consisted of two treated rings with both inner and outer walls of the duct also treated. The aft fan duct wall treatment consisted of three different thicknesses to suppress a broad range of frequencies. The core exhaust duct consisted of a bulk absorber material of two different thicknesses.

The objective of the tests was to obtain noise data for a heavily suppressed, high-bypass turbofan suitable for a STOL externally blown flap (EBF) aircraft. The design fan inlet suppression was about 30 dB and the aft fan suppression 37 dB. The design core exhaust suppression was about 25 dB. The results of the tests indicated an overall noise reduction of 23 PNdB with a reduction of 35 dB in the far field for the fan blade passing frequency. Fan pure tone narrow band noise reductions were as high as 50 dB in the far field (fig. II-28). Performance losses due to the suppressed nacelle were about 15 percent. Calculations made for splitter designs that have been optimized for aerodynamic performance indicate that the total takeoff thrust loss at maximum power should be approximately 8 percent.

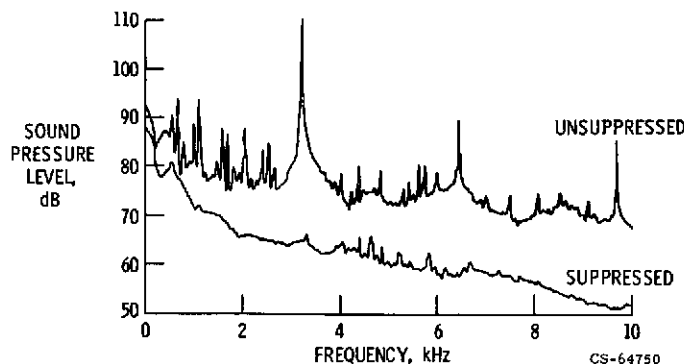


Figure II-28. - TF-34 noise spectra at 100 ft. SLS fan speed, 7140 rpm; angle from inlet, 60°.

The suppressors for the NASA quiet engine will be tested further at Lewis. An attempt will be made to determine the actual noise attenuation provided by these suppressors. This will be done by using internal noise measurements and fan-alone tests.

Theoretical work on noise suppressors is continuing to provide a better understanding of dissipative suppressors and to provide better design techniques. This will involve both in-house efforts and outside grants and contracts. The theoretical effort will be both in analytical extensions as well as a new numerical technique which has recently been initiated. These extensions should provide a more realistic model for the sound propagation in suppressors with cross-sectional variations and steady flow gradients. It is anticipated that by using the velocity gradients in an ingenious manner the suppressors can be made much more efficient and thus reduce the aerodynamic losses.

Experimental studies with sonic (or choked) inlets have been conducted at Lewis and at Boeing-Seattle under NASA contracts. The Lewis work, which has used a  $5\frac{1}{2}$ -in. fan in the past, will be extended by extensive testing with a 12-in. duct in the near future. The Boeing studies have used a 12-in. fan and the JT3D engine.

The results of these studies have demonstrated that the choked inlet can provide very high attenuations of the forward radiated fan noise while incurring only small losses, provided the diffusion angles are kept sufficiently small. Similar results were obtained at NASA and Boeing and can be summarized as follows. With a translating centerbody inlet at static ambient conditions, the noise reduction obtained was 29 dB at the blade-passage frequency with large reductions throughout the noise spectrum. These results were accomplished with only a 1.5 percent loss in total pressure. The low-pressure losses quoted for the choked inlet are a result of using low diffusion angles between the inlet throat and the fan face. If the flow variations between cruise, takeoff, and approach power settings are very small (as in STOL applications), then these diffusion angles can be accommodated in a reasonable length of inlet. However, for CTOL aircraft, the flow variation (and thus area ratio variation) is quite large and the flow in short inlets will separate and cause large total pressure losses. The long inlets required will result in increased friction losses along the wetted surfaces and will increase the weight of the nacelle.

With an ambient velocity of 150 ft/sec and an angle of attack of  $35^\circ$ , the noise reduction at the blade-passage frequency was 22 dB again with only a 1.5 percent loss in total pressure. However, in addition, the airflow distortion at the face of the fan tends to increase with both inlet Mach number and angle of attack. This is a factor which must be given careful consideration with regard to fan stall limits. Both the static and crossflow noise measurements were limited by noise floors at the maximum flow rate. The length-to-diameter ratios of these inlets were about 1.

A full-scale, choked inlet will be tested on quiet engine C at Lewis. This is a CTOL engine and will require a long inlet. Scale-model tests will be made on a 12-in. inlet at Langley Research Center in an anechoic chamber to select the L/D for the full-sized inlet. The L/D variation will be from 1.4 to 1.85 on this scale model. These models will later be tested at Lewis in a wind tunnel with cross flow.

The theoretical work mentioned earlier in connection with dissipative liners will also be useful in obtaining a better understanding of the acoustic performance of an actual choked inlet with its axial, radial, and transverse velocity gradients.

The large noise attenuations obtained with dissipative suppressors are not obtained without performance penalties. A continuing effort is being maintained to reduce these losses without giving up the noise attenuation. In any application, a decision will have to be made on the delicate balance between what goals are desirable and what economic penalties are acceptable. The perforations necessary in any lining material will increase the skin friction over that of a smooth plate. Current estimates are an increased

skin friction for perforated sheet metal of 50 percent and for woven structures about 85 percent. The addition of splitter rings in an engine nacelle increases the losses in three ways: (1) the wetted area of the added acoustic material on the splitter rings increases the friction-drag loss; (2) the rings are immersed in high-velocity air and have form drag; and (3) the available flow area is reduced by the cross-sectional area occupied by the rings, thereby increasing the steady-flow Mach number. This increases the total pressure losses as the square of the Mach number. The Mach number can be kept down by expanding the nacelle cross section, but this then increases the external drag at cruise. The increased weight of the nacelle also represents an economic loss since it reduces the payload.

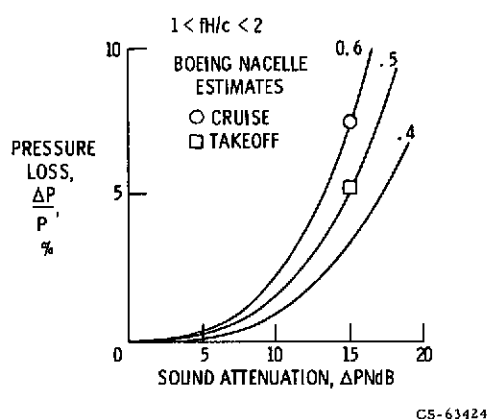


Figure II-29. - Estimated pressure loss due to suppression.

The total pressure loss versus noise reduction can be illustrated as in figure II-29. As discussed earlier, this illustration may be somewhat pessimistic, but it certainly illustrates the trends correctly. Small initial noise reductions (5 to 10 PNdB) can be obtained quite efficiently. The baseline engine will have blade-passage tones and harmonics and even low frequency multiple-pure tones standing out beyond the broadband noise level. These tones tend to concentrate near the outer wall and are very susceptible to outer cowl treatment only. The only penalties involved in a moderate reduction of these tones are the increased skin friction and possibly additional weight of the outer cowl. The perceived noise level is reduced almost directly with the reduction of dominant tones in the frequency range of greatest ear sensitivity (3000 to 4000 Hz). However, once these dominant tones have been reduced, other parts of the spectrum become dominant and a much broader frequency range must be attacked by the suppressor. This requires the use of several different wall structures to reduce these wide ranges of frequency and ultimately the use of splitter rings if the attenuation required is large. When this occurs, the pressure losses begin to rise rapidly as shown in figure II-29. It is apparent

that there is considerable incentive to make these dissipative suppressors much more effective than present technology indicates.

Present research efforts are directed at making noise suppressors much more efficient. Emphasis is being placed both in theoretical and experimental programs. The theoretical models are being extended to treat noise propagation with dissimilar wall constructions, area variations, and steady flow velocity gradients. It is anticipated that better use of reflection and refraction phenomena will greatly increase the efficiency of noise suppressors.

The use of axial and radial velocity profiles within a dissipative suppressor leads to a type of hybrid suppressor. This hybrid utilizes the best properties of both the dissipative liner and the choked inlet. The velocity gradients might be used to refract the sound waves into the wall where they might be absorbed. Perhaps a suppressor without splitter rings, hard choking, or variable geometry may be realized with such a configuration. Preliminary data taken by General Electric on a high velocity inlet suppressor indicates the approach has merit. A hybrid suppressor will be tested at NASA Lewis Research Center.

## Engine System Noise

The preceding discussion has dealt with several components of engine noise. The concern, however, is with the noise that we hear, that is, total engine noise. What we hear today is generally fan noise. It is currently the loudest single noise source and thus it dominates in establishing the noise of the total system. Progress has been made in reducing fan noise and further progress will lower the total engine system noise, but only to a point at which another contributor, such as core-jet noise, becomes dominant. By increasing the engine bypass ratio, we can (within certain cycle limitations) reduce the jet noise by extracting more energy from the core jet, thereby reducing its velocity. Coupled with other jet-noise-suppression techniques, the overall engine noise level may then be reduced until another source of noise becomes dominant; perhaps turbine noise or possibly fan noise again will become dominant and set the total noise level. It is likely that we are today progressing in our research to the point at which combustor and turbine noises will shortly become the determinants of total engine noise. These are accordingly moving up in priority for future research effort.

Reducing the total system noise of an engine also involves several complex interactions. For example, if higher bypass ratio is used to reduce core jet noise, the turbines may have to be more highly loaded, thereby increasing the turbine noise. Such interactions must be carefully weighed in the engine design to achieve a best compromise and a minimum noise for the total engine. In a similar vein, the performance or economic penalty of each potential noise reduction feature must be carefully balanced

against the noise benefit to be gained.

In recognition of these superimposed effects and interaction problems, coupled with the many judgments and economic compromises involved, NASA has undertaken the building and testing of complete research engines wherein the noise reduction features are required to function in a real and total environment. In this way any unexpected difficulties may be brought to light and solved such that the industry may incorporate such features in future engines with reasonable risk. The NASA quiet engine, refan, and quiet clean STOL experimental engine (QCSEE) are examples of this approach.

### NASA Quiet Engine Program

The NASA Quiet Engine Program was initiated about 5 years ago with the objectives of developing engine noise reduction technology and demonstrating in engine tests the combined effect that this technology would have on reducing engine noise. An additional objective was to determine the impact on airplane economics resulting from the measures necessary to reduce the noise.

In figure II-30 the major elements of the overall quiet engine program are shown along with a schedule. The engine design definition studies determined the engine cycle, mechanical arrangements, and other characteristics required to achieve the noise goals set for the quiet engines. Following these studies a contract was initiated in mid-1969 for the design, fabrication, and testing of two quiet engines. In parallel with the engine program a contract with the Boeing Company was initiated to provide NASA with an acoustically treated, flight-type nacelle for testing on one of the quiet engines. The acoustically treated nacelle was tested at NASA Lewis, as part of the in-house program, to determine quiet engine noise levels with full fan noise suppression.

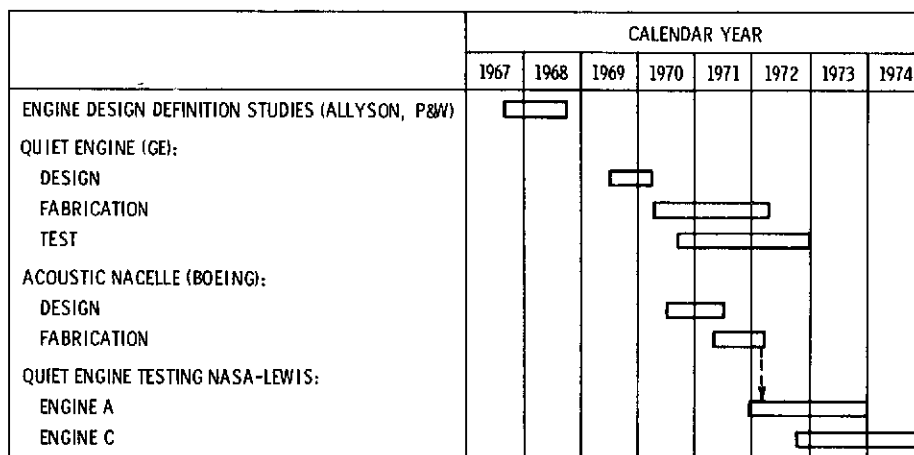


Figure II-30. - Quiet engine program.

The turbofan engine, which is the type commonly used in the current transport fleet, has two major noise sources. They are jet noise and turbomachinery noise. The noise reduction features incorporated into the quiet engine designs to counteract these two noise sources are shown by the following:

Jet noise:

- (1) High bypass ratio 5-6, gives low jet velocity and low jet noise

Fan source noise:

- (1) Large spacing between fan rotor and stator, reduces interaction noise
- (2) Low tip speed (1160 ft/sec), reduces fan noise production
- (3) High tip speed fan (1550 ft/sec), requires additional suppression for low noise but improves engine weight
- (4) Optimum ratio of fan stator to rotor blades

Fan noise suppression:

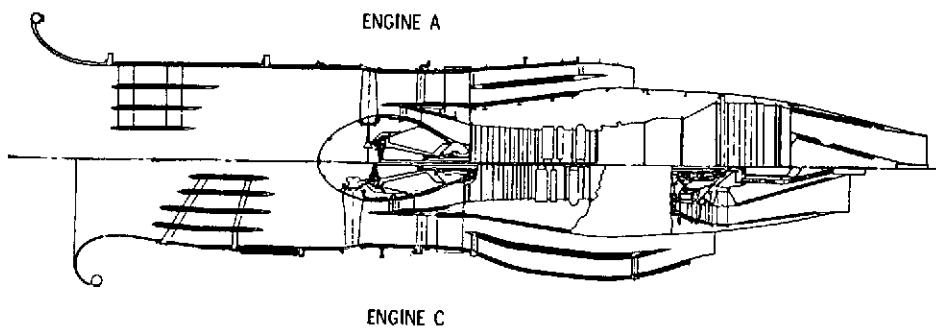
- (1) Sound absorbing liners in fan inlet and discharge ducts

A high bypass ratio engine was chosen to reduce jet velocity and consequently jet noise. A number of features were incorporated to reduce fan noise production. A relatively large rotor-stator spacing of two rotor chords was employed to reduce fan discrete frequency noise. A choice of rotor tip speeds was available for the fan design. Low tip speed fans have been found to produce less noise, while high tip speed fans can improve airplane economics by reducing engine weight, but they require additional noise suppression to achieve equally low noise output. Both approaches were evaluated in this program. Finally, a noise governed optimum ratio of number of fan stator to rotor blades was employed. The ratio was 2.25. In addition to design features aimed at low fan noise production, the fan noise can be reduced further by the addition of sound absorbing liners to the inlet and outlet ducts. This was also investigated on the quiet engines.

A cross section of quiet engines A and C with full fan acoustic treatment applied is shown in figure II-31. Also shown are some of the important performance and design characteristics of the engines. Both engines were designed to produce 22 000 lb of thrust, and this puts them in the thrust class of the JT3D engines used in the DC-8 and 707 type aircraft. Engine C, the high-speed engine, has a single stage fan with a design fan tip speed of 1550 ft/sec, while engine A, the low speed engine, has a single stage fan with a tip speed design point of 1160 ft/sec. To obtain a major cost saving, both engines use the CF-6 engine core, and for this application it is oversized; therefore, the engines are not flight weight. The low speed turbines on the CF-6 cores had to be modified as indicated to meet the power and speed requirements of the fans.

The acoustic performance of the quiet engine was determined for both unsuppressed and suppressed conditions. The results of the baseline, or unsuppressed, engine tests





	ENGINE A	ENGINE C
FAN PRESSURE RATIO	1.5	1.6
BYPASS RATIO	6.1	5.1
THRUST, LB	22 000	22 000
ENGINE CORE	CF-6	CF-6
FAN TIP SPEED, FT/SEC	1160	1550

Figure II-31. - NASA-GE quiet engines with full suppression.

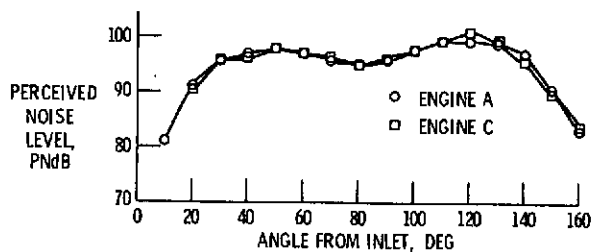


Figure II-32. - Baseline engine perceived noise directivity. Approach speed, 370-ft sideline.

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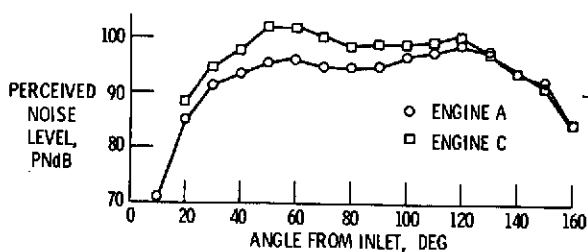


Figure II-33. - Baseline engine perceived noise directivity. Takeoff speed, 1000-ft sideline.

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are shown in terms of perceived noise in figures II-32 and II-33. Figure II-32 gives data for the approach engine speed while figure II-33 represents takeoff engine speed. These data show that the noise levels of both engines are quite similar except for the takeoff speed in the front end of engine. Here the high-speed engine noise is about 7 PNdB higher, and this increase is a result of the "multiple pure-tone" noise associated with the supersonic operation of the fan blade tip.

Since the baseline engines are dominated by fan noise, adding fan suppression in terms of wall and splitter acoustic treatment (see fig. II-31) significantly reduced engine perceived noise levels. However, engine C, the high speed engine, requires additional acoustic treatment in both the fan ducts and the core nozzle in order to obtain noise levels as low as engine A. This is a result of the higher fan noise and also a higher turbine noise level associated with the high engine speed operation.

Projections of the quiet engine ground static test data to aircraft flyover conditions were made to compare these results with current aircraft. Since the thrust of the quiet engines is in the class of the engines used on the DC-8 and 707, the comparison was made using the DC-8 airplane. The noise results are expressed in terms of effective perceived noise level (EPNdB) which is the noise unit used by the FAA for regulating aircraft noise. The results are shown in table II-1. Measurements of the DC-8 aircraft

TABLE II-1. - FLYOVER NOISE COMPARISON

	Takeoff	Approach
	EPNdB	
DC-8	116	118
FAR-36	104	106
Baseline quiet engine A	97	98
Quiet engine A with acoustic nacelle	90	89

noise at the takeoff and approach measuring stations show noise levels of 116 and 118 dB, respectively. These numbers compare with FAR-36 limits of 104 and 106, respectively. The baseline (unsuppressed) quiet engine A is seen to be some 7 to 8 dB lower than current FAR-36 regulations and about 20 dB below the DC-8. Furthermore, the addition of an acoustically treated nacelle lowers the noise levels another 7 dB. These results clearly indicate that the potential for lower noise levels of future aircraft is good; however, it is also necessary to consider the impact that lowering noise levels will have on aircraft economics.

A study of this nature was performed using a 200 000-lb gross weight trijet as a typical aircraft. The results of this study are shown in figure II-34. Here direct oper-

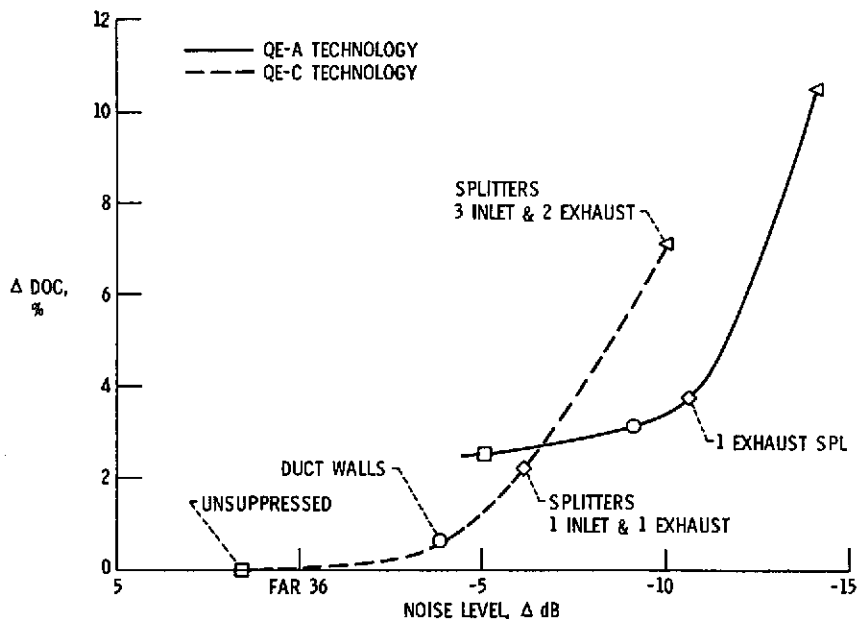


Figure II-34 - Comparison of quiet engine A and C economics with variable fan suppression  
200,000 lb, tri-jet.

ating cost (DOC) is plotted against aircraft noise level relative to FAR-36 noise regulations for both the high-speed and low-speed engines. The curves shown for each engine represent various degrees of fan acoustic treatment starting with an unsuppressed case on the lower end of the curves and ending with wall treatment plus three inlet and two exhaust splitters at the upper end. The higher speed engine is more economical (-2.5 percent DOC) in an unsuppressed condition because the high engine speed allows the number of turbine and compressor stages to be reduced, thereby reducing engine weight. However, it produces more noise as stated previously. The knee in the curves (where DOC begins to increase rapidly with noise reduction) results from increased engine weight and engine pressure losses that accrue as acoustic splitters are added to the fan inlet and exhaust ducts. As a result, the low speed engine (A), even though it is a basically less efficient engine, is more economical as lower noise levels are reached. The cost of obtaining a noise level of FAR-36 - 10 PNdB, using the A type engine, is seen to be about 4 percent in DOC.

It is obvious, however, that to progress beyond the FAR-36 - 10 PNdB noise levels economically a vigorous noise reduction technology program is required. Advances in noise source reduction and improved suppression efficiency are areas of major importance for future technology programs. The fan and possibly the turbine are the primary candidates for source noise reduction programs. Improvements in suppression technology are needed to increase acoustic treatment effectiveness so that less treatment

will be required for a given noise reduction and also to reduce the weight per unit area of treatment by incorporating new materials or fabrication concepts or both. The use of a sonic inlet also is a promising technique for reducing the cost of noise suppression. This concept will also be evaluated in future programs.

#### NASA Refan Program

The Refan Program applies current source abatement technology to the engines that power the narrow-body aircraft in the U.S. civil fleet. These narrow-body aircraft (707, 727, 737, DC-8, and DC-9) introduced into service beginning in the late 1950's are the noisiest aircraft in the civil fleet. Previously developed noise reduction technology is being applied to the propulsion systems of these aircraft. No advances in the state-of-the-art are anticipated. The program objectives are to demonstrate through development of retrofit kits that the noise produced by the narrow-body fleet can be reduced to 5 to 10 EPNdB below FAR-36 while retaining demonstrated engine reliability and maintainability, causing no degradation of aircraft performance or safety, and all at an acceptable fleet retrofit cost. Close coordination of the program is being maintained with the Department of Transportation through the Joint DOT/NASA Office of Noise Abatement. This office is using input data from both this program and from the FAA Acoustic Nacelle Program to assess the costs and benefits of the retrofit options.

Four approaches or combinations of approaches are possible for reducing the noise exposure in the near-airport environment using currently available technology:

- (1) Retirement of the narrow-body fleet
- (2) Nacelle acoustic treatment
- (3) Engine and nacelle modifications
- (4) A completely new engine

Early replacement of the narrow-body fleet with quieter wide-body aircraft to maintain the present capacity is estimated to cost on the order of \$8 billion. Thus, early retirement of the narrow-body fleet appears to be prohibitively expensive. Considerable technology effort has been applied to a completely new engine through the NASA Quiet Engine Program. Development of a completely new quiet engine, however, is being considered primarily for new aircraft. This option would be extremely costly, particularly in view of the limited life remaining in these aircraft. A new engine would also prove difficult to install particularly on the JT8D-powered aircraft - 727, 737, and DC-9. An extensive technology effort has also been applied to nacelle treatment through early NASA work on acoustic nacelles for the 707 and DC-8 aircraft and through the current FAA program in which all five narrow-body aircraft are being considered. This approach is limited in the amount of noise reduction achievable, particularly during take-off, and it results in some performance degradation of the aircraft.

The NASA Refan Program deals with the third option - engine and nacelle modifications. This approach is attractive since it would not result in the performance loss associated with nacelle treatment only, would be less costly than a completely new engine, and would provide substantial noise relief to the airport community. It also might afford a convenient opportunity to install a retrofit combustor on JT3D engines to reduce smoke and other emissions while the aircraft are undergoing a refan modification. The JT8D engines already have a "smokeless" combustor that has been retrofitted to U.S. aircraft.

Technical approach - The objectives of the NASA Refan Program are to be accomplished by developing retrofit kits which when installed will result in significant reductions of the two main sources of engine noise. These sources are the turbomachinery noise generated by the interaction of the air with the rotating and stationary blade rows, principally in the fan stage, and the jet noise generated downstream of the engine where the exhaust jet mixes with the surrounding atmosphere.

Fan turbomachinery noise is reduced by use of a single-stage fan with greater spacing between the rotating and stationary stages than exists in the current two-stage fans, and by proper selection of the number of rotor blades and stator vanes for minimum noise generation.

The jet noise problem is attacked by reducing the velocity of the jet exhaust. This is accomplished by extracting more work from the turbine to drive a larger diameter fan. The larger fan results in a larger bypass-ratio engine which generates slightly more thrust at lower jet exit velocity. Additional noise reduction beyond that obtainable from engine modifications will be obtained by lining the internal surfaces of the engine nacelle with sound absorbing material and possibly by using acoustically treated inlet splitter rings.

History - The Refan Program was initiated in August 1972. The scope of the program encompassed noise and pollution reduction for the JT3D and JT8D engines. The JT3D engine powers the 707 and DC-8 aircraft and the JT8D powers the 727, 737, and DC-9 aircraft. Phase I contracts were let for design and analysis of the engine and nacelle modifications with three major contractors: Pratt & Whitney Aircraft, a Division of United Aircraft Corporation; The Boeing Company; and the Douglas Aircraft Company, a Division of McDonnell Douglas Corporation. Small contracts were also let with American Airlines and United Air Lines for consulting work to assure that the modifications being considered incorporate as many of the user airlines' requirements as possible.

In January 1973, program funding curtailment forced limiting the scope of the program to only one engine. The joint NASA/DOT/FAA decision was to proceed with the JT8D rather than the JT3D. The basic reason for this decision was that the JT8D-powered aircraft will have a larger impact on the aircraft noise exposure in the 1980's. There was no technical reason for deferring further work on the JT3D. The modified

JT3D-9 engine appeared to be a low technical risk development. The design definition that was completed on the engine and the DC-8 and 707 installations had indicated no significant problems to be expected in implementing a retrofit of these aircraft.

Program status - Currently the three major contractors are progressing on schedule with the design of JT8D modifications and installation designs for use of the refanned engines on the 727, 737, and DC-9 aircraft. The overall engine design modifications have been selected and are shown in cutaway compared to the existing JT8D engine in figure II-35. The two-stage fan is replaced with a single-stage fan with approximately a

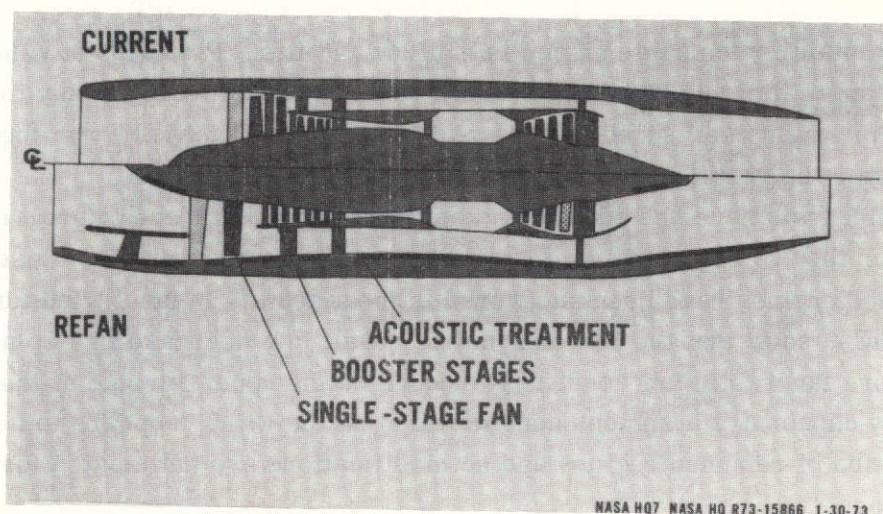


Figure II-35. - JT8D engine.

two-chord spacing between the rotor and exit guide vanes. The core engine pressure ratio and flow capacity are maintained by inserting two core booster stages in front of the low pressure compressor to compensate for loss of the pressure-producing capability of the second fan stage in the core region. Because of the additional swirl of the exit flow caused by the increased work output of the turbine, a slight recambering of the fourth stage turbine rotor blade is required to reduce the swirl angle. The acoustic treatment is shown schematically. Trade studies are being conducted by the airframe contractors to determine the optimum amount of acoustic treatment to use considering noise, aircraft performance, and cost.

The effects of these engine modifications on some key engine parameters are shown in table II-2 where the refanned JT8D is compared to the current engine. The larger diameter fan results in more airflow, a larger bypass ratio, and an increase in fan tip speed. The higher tip speed will generate noise in the form of multiple pure tones which previous technology development efforts show can effectively be suppressed with acoustic treatment. The engine cycle temperature has been selected to remain unchanged in the

TABLE II-2. - JT8D ENGINE CHARACTERISTICS

	Current JT8D-9	Refan JT8D-109
Fan tip diameter, in.	40.5	49.2
Sea level airflow, lb/sec	319	467
Bypass ratio	1.05	2.04
Fan tip speed at takeoff, ft/sec	1420	1600
Cycle temperature, °F	1880	1880
Primary jet velocity, ft/sec	1766	1479

interest of maintaining the same engine reliability and life. Primary jet velocity has been lowered approximately 300 ft/sec. This velocity reduction is the key to the decrease in jet mixing noise. Mixing of the core flow more effectively with the fan bypass flow would lower the resultant exit velocity and jet noise even more.

Wind tunnel tests have been completed on DC-9 models and are in progress on the center duct for the 727 aircraft. No installation problems resulting from use of the larger refanned engines have been uncovered in these tests. In fact, wind tunnel model tests on the DC-9 show that the larger nacelles result in a decrease in airplane drag because of a more favorable flow conditions induced on the upper surface of the wing. Deep stall recovery capability, a serious consideration on the DC-9, appears to be adequate after installation of refanned engines and no modifications are anticipated for the tail control surfaces.

Aircraft performance with refanned engines depends greatly on the amount of acoustic treatment employed. Table II-3 presents a list of parameters for the 727 aircraft and the range of changes that can be expected when the 727 is retrofitted with refanned engines. Not until a final nacelle configuration is selected and more component tests are completed can firm performance numbers be quoted. However, in general, it can

TABLE II-3. - 727 AIRCRAFT PERFORMANCE

## CHARACTERISTICS

	Current	Refan, percent change
Installed takeoff thrust per engine, lb	12 700	5.7 to 10.0
Cruise thrust specific fuel consumption, (lb/hr)/lb	0.83	-3.4 to +2.4
Operating empty weight, lb	99 000	2.0 to 4.1
FAR takeoff field length, ft	8370	-3.5 to -8.4
Range at 30 000 ft (M = 0.84), n. mi.	1355	<sup>a</sup> 0 to -20.

<sup>a</sup>Recertified for higher gross weight.



be said that with refanned JT8D engines, aircraft takeoff thrust will be increased; specific fuel consumption at cruise will be slightly better or slightly worse than for current aircraft depending on the amount of nacelle acoustic treatment used; the operating empty weight will be greater due to heavier engines and nacelles; takeoff field length requirements will be less due to the increased thrust; and aircraft range for the vast majority of the current route structure operations will be unaffected. If range loss should be a problem for certain operators using these aircraft at maximum range, aircraft recertification at a higher gross weight to recover the range with additional fuel does not appear to be a problem.

At the time of termination of the JT3D portion of the program, work on the JT3D had progressed into the final engine design stage. The engine layout design has been completed. The engine and its installation in 707 and DC-8 aircraft are judged to be entirely feasible from a technical standpoint. Engine and airplane characteristics are summarized in tables II-4 and II-5. Presently, the contractors are in the process of writing summary reports on the JT3D part of the program.

Acoustic performance of the aircraft retrofitted with refanned engines has been estimated and updated continuously throughout the course of the program. The improvements in noise will be discussed in a later section on benefits.

TABLE II-4. - JT3D ENGINE PERFORMANCE CHARACTERISTICS

	Current JT3D-3B	Refanned JT3D-9
Fan tip diameter, in.	50.2	56.6
Sea level airflow, lb/sec	460	609
Bypass ratio	1.36	2.25
Fan tip speed at takeoff, ft/sec	1423	1529
Cycle temperature, °F	1703	1741
Primary jet velocity, ft/sec	1580	1380

TABLE II-5. - 707 (JT3D) AIRCRAFT PERFORMANCE CHARACTERISTICS

	Current JT3D-3B	Refanned JT3D-9	Performance change, percent
Installed takeoff thrust per engine, lb	15 370	16 720	+8.8
Cruise thrust specific fuel consumption, (lb/hr)/lb	0.85	0.82	-3.2
Operating empty weight, lb	145 000	148 920 to 149 560	2.7 to 3.1
Maximum taxi weight, lb	336 000	336 000 to 341 050	0.0 to 1.5
FAR takeoff field length, ft	11 350	10 250 to 10 680	-9.7 to -5.9
Range, n.mi.	4770	4630 to 4770	-2.9 to 0.0



Program plans and schedule - Current Refan Program plans are to proceed with development of JT8D retrofit kits for use on 727, 737, and DC-9 aircraft consistent with a \$40 million funding authorization through FY 1975. The program scope for phase II is presently being considered in view of the decreased funding from the earlier plan of \$55 million. Demonstration ground tests and flight tests on one or more aircraft are being considered.

The first major component test will take place in April at Pratt & Whitney where a full-scale fan will undergo acoustic tests. The effectiveness of various amounts of acoustic treatment will be demonstrated as well as the overall design concept of the fan. The fan to be used was originally designed for the JT3D engine. However, by the addition of inlet guide vanes and some rework of the fan exit guide vanes, the JT8D fan can be closely simulated.

In November, the JT8D fan will be tested together with the low-pressure compressor spool to determine aerodynamic performance. During this same time frame, wind tunnel tests on inlets and nozzles as well as scale-model fan acoustic tests will be conducted.

Refanned JT8D engine ground tests are scheduled to begin in January 1974 with mating to an acoustic nacelle to take place early in the engine ground test program. Engine performance and acoustic signatures will be established.

Benefits - Obviously the reason for engaging in a retrofit program such as this is to provide a means of improvement in the near-airport noise environment. The Joint Office of Noise Abatement in a cost/benefit analysis is studying the relative benefits and costs associated with various retrofit options. Aircraft noise data at FAR-36 measuring points and aircraft noise levels as a function of slant range from an overflying aircraft are used as input data for their analysis. Table II-6 shows the FAR-36 measuring point data for the current narrow-body aircraft and for refanned aircraft with maximum acoustic treatment. Also shown are the levels required to meet the current noise regulations. The refan numbers are the best estimates based on noise data from past experience gained in noise technology programs. They show that substantial improvements in the noise of aircraft, in fact considerably better than FAR-36 requirements, are possible.

A more meaningful measure of the improvements to be realized by refanning is presented when noise footprints on the ground are considered. The area within a noise footprint contour represents the area which would be exposed to that given noise level or higher. Footprints should be viewed as qualitative comparisons of noise exposure rather than absolute measures of the area or people affected. Figures II-36 and II-37 are 90 EPNdB footprints for the 727 and 707 aircraft, respectively. The current aircraft and aircraft retrofitted with refanned engines in acoustic nacelles are compared. Significant reductions in area are evident. Figure II-38 shows 95 EPNdB footprints for the current and refanned 727 aircraft superimposed on O'Hare Airport. The area subjected

TABLE II-6. - AIRCRAFT NOISE LEVELS

Aircraft	Measurement location	Baseline	Refanned	FAR-36
		EPNdB		
727-200	Sideline	102	92	104.5
	Takeoff/cutback	102	88	100
	Approach	109.5	96	104.5
737-200 (advanced)	Sideline	104	92	103.5
	Takeoff/cutback	96	84	96.5
	Approach	108	95	103.5
DC-9-32	Sideline	101.5	92	103.5
	Takeoff/cutback	97	84	96
	Approach	108	95	103.5
DC-8-61	Sideline	103	94	105.5
	Takeoff/cutback	117	95	103.5
	Approach	117	98	105.5
707-320B	Sideline	107.5	94	106.5
	Takeoff/cutback	113	95	104
	Approach	119.5	98	106.5

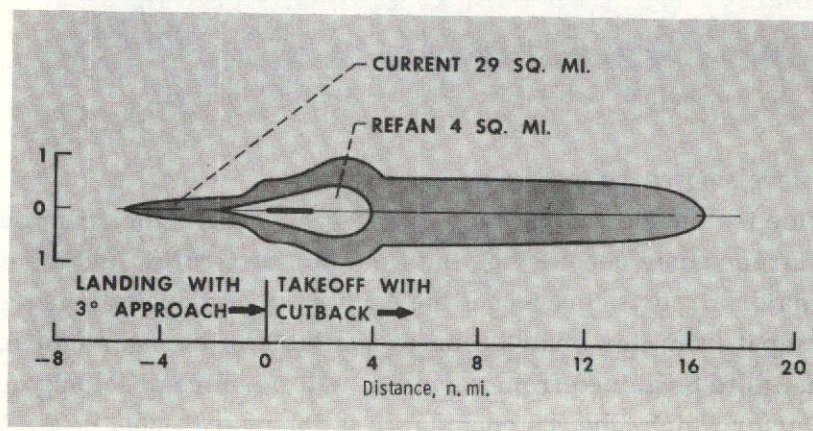


Figure II-36. - 90-EPNdB contours for 727 aircraft.



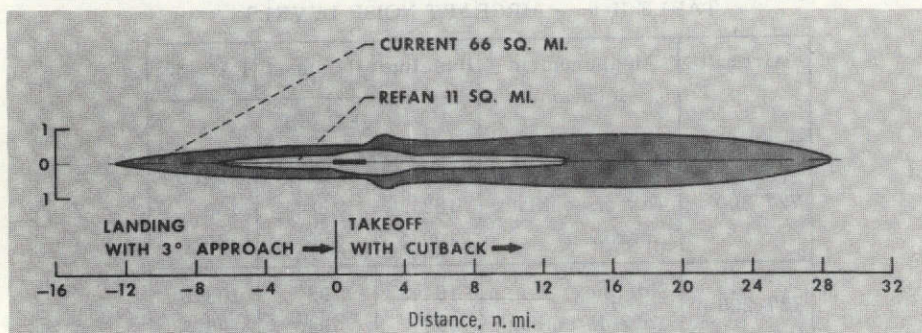


Figure II-37. - 90-EPNdB contours for 707 aircraft.



Figure II-38. - Noise contours at O'Hare for 95-EPNdB 727 aircraft.

to this high noise level is greatly reduced.

The Joint Office is considering not only single event footprints but is also studying the problem on a larger scale considering the fleet mix of aircraft and the number of operations at 23 major airports throughout the country in terms of a noise exposure forecast (NEF). As output from this study becomes available in the near future, a clearer picture of the benefits to be gained from refanning will be more precisely quantified.

Costs - One factor which must be considered is the overall cost of a retrofit alternative and how the cost will be absorbed. This is being considered in depth in the Joint Office studies. Preliminary estimates of retrofit kit costs for refanning have come from the contractors and indicate that a three-engine retrofit would cost about \$1.4 million per aircraft, a two-engine aircraft about \$1.0 million, and a four-engine aircraft about \$1.8 to \$1.9 million.

The total cost of a U.S. fleet retrofit with refanned engines is equivalent to the capital that would be generated by a 1 to 2 percent surcharge on tickets over the next 5 to 10 years. To put this number in perspective, it should be recalled that there is already

an 8 percent tax levied on tickets used to build a trust fund for airport development.

Summary - The objective of the NASA Refan Program is to develop propulsion system retrofit kits for the aircraft in the narrow-body fleet. Installation of these retrofit kits would result in substantial reductions in aircraft noise levels and in noise-impacted areas. Funding constraints have forced NASA to defer further government funded work on the JT3D. The layout design of the modified JT3D is complete and preliminary installation designs have been completed. With the presently planned government resources NASA will concentrate future effort on the JT8D. No technical problems are evident which would hinder development of either JT8D or JT3D retrofit kits. The Joint DOT/NASA Office of Noise Abatement is assessing the costs and benefits of various retrofit options. The refan option is more effective in terms of noise reduction but also is more costly to implement than a retrofit with nacelle acoustic treatment.

A bibliography of pertinent reports on this subject is included at the end of this chapter.

## AIRCRAFT NONPROPULSIVE (AIRFRAME) NOISE

Airframe noise is defined as the noise generated by an aircraft in flight from sources other than the engine, auxiliary power units, and machine accessories. Airframe noise or aircraft nonpropulsive noise sources, as illustrated in figure II-39, thus include noise generated by airflow over the fuselage, wings, nacelles, flap systems, landing gear struts, wheel wells, etc. The NASA and Navy funded an experimental program (ref. 14) to measure the airframe noise for five small airplanes in the gross weight range 1500 to 39 000 lb during low-altitude power-off flyby operations. The

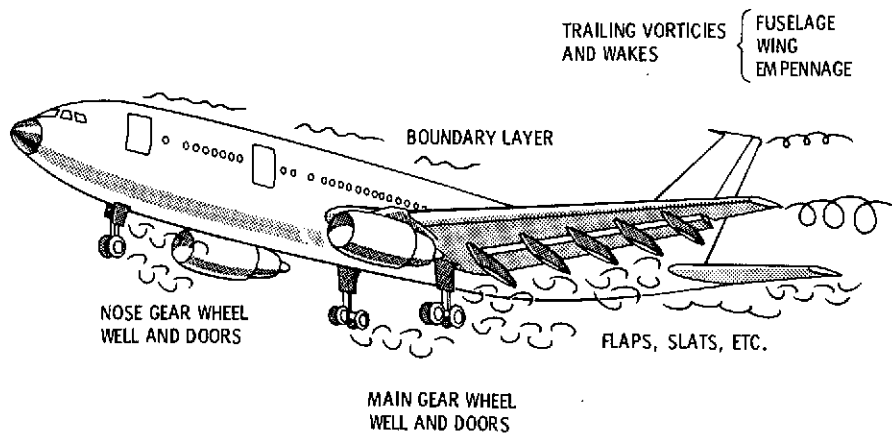


Figure II-39. - Schematic diagram illustrating sources of aircraft nonpropulsive noise sources.

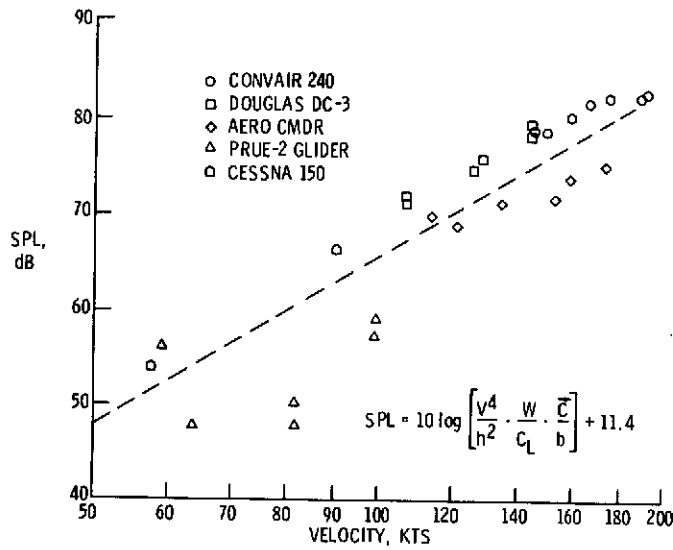


Figure II-40. - Summary of power-off aerodynamic noise levels for several aircraft as a function of forward velocity in knots. (See ref. 14.)

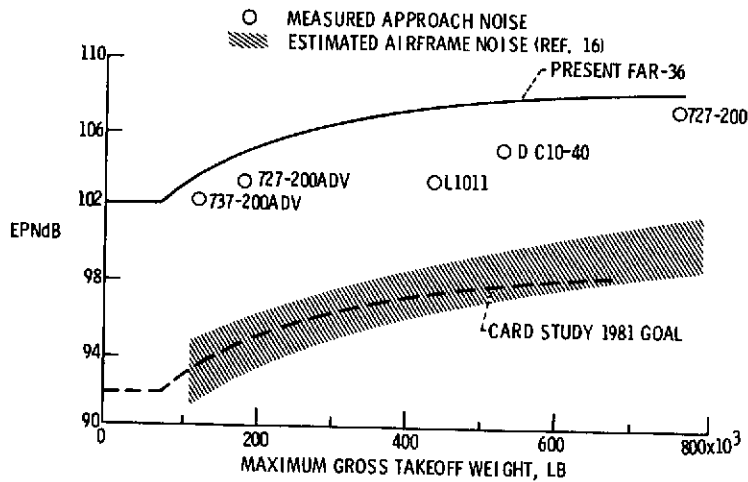


Figure II-41. - Measured and predicted noise levels for several current aircraft.

power-off aerodynamic noise levels which have been normalized to an altitude of 500 ft are shown plotted as a function of velocity in figure II-40. These aircraft were in relatively clean condition because of gears and flaps retraction with the exception of the Cessna 150, which had a fixed gear. An empirical relation for noise predictions based on this experimental information was provided and is shown in the lower part of figure II-40. An extrapolation of these data to larger airplanes suggests that the airframe noise can conceivably be the noise floor for future large airplanes for which substantial engine noise treatment has been used. Further data are required on larger aircraft to evaluate this extrapolation. Some of these will be obtained in tests at the NASA Flight Research Center later this year.

In figure II-41 are presented estimated and measured approach noise levels for several current airplanes compared to those specified in FAR-36. The circle symbols represent certified landing approach noise levels. It is noted that these aircraft generate noise levels which are less than those specified in FAR-36 (from 2 to 5 EPNdB). The lower dashed curve which is situated 10 EPNdB below the levels of the present noise certification ruling represents the CARD 1981 goal (ref. 15). The hatched region is defined in reference 16 as including the airframe noise levels for the aircraft of the figure as estimated by the method of reference 14. Recent unpublished data from the Lockheed-Georgia Company and the USAF for the C5-A tends to confirm the validity of the hatched region. The main conclusion of the figure is that the noise associated with all of the nonpropulsive sources (no engine) appear to lie about 10 dB below the noise levels of the present noise certification ruling and could in fact be the limiting noise floor relative to reducing noise levels to and below the 1981 CARD goal (ref. 17), until the nonpropulsive noise is itself reduced.

A program to understand and reduce the nonpropulsive noise is underway at NASA. Basic studies are planned on full-scale aircraft and complete models and model components for quiet wind tunnel tests. These studies will provide information relative to the identification and location of airframe noise sources; the manner in which noise varies as a function of angle of attack, local air velocity, turbulence levels, separated flows, etc.; improved prediction methods; and approaches to noise alleviation. Initial studies will be carried on in quiet wind tunnel facilities such as those in the Langley Aircraft Noise Reduction Laboratory and these studies will eventually identify concepts for full-scale testing on aircraft and gliders.

The components of airframe noise are judged to be associated with turbulent flows and flow separation and hence prediction methods will inherently involve empiricism. Empirical constants used in the predictions will be evaluated in experimental studies. At this time the problem of scaling frequencies and amplitudes of disturbances associated with unsteady flows is not well enough understood. It is believed that a series of measurements of the fluctuating surface pressures on airfoils and fuselage under a variety of inflow conditions and for known localized flow situations will be required. To de-



velop systematically the empirical constants needed for prediction, some tests in conventional wind tunnels at varying model scales may also be required for the prediction of the fluctuating surface pressure patterns. Measurements are required in such studies to define the mean flow patterns and the fluctuating flow patterns, as well as the surface pressure fluctuations.

Selected experiments are planned in quiet wind tunnel facilities as well as conventional facilities to establish validity of the data. In addition, quiet wind tunnel facility tests will be planned to correlate the surface pressure fluctuations with the radiated sound field for a variety of fuselage and wing flap flow situations.

## SUPERSONIC TRANSPORT AIRCRAFT

The supersonic transport (ST) has two associated environmental noise problems that are of serious concern with regard to public acceptance. These are the noise from the engines during landing, takeoff, and ground operations at airports and the sonic booms resulting from flight operations over inhabited areas at Mach numbers higher than 1.0. These problems are different in nature and require different approaches for noise control.

Contained herein are discussions of jet engine noise control approaches involving variable engine cycles and such suppression devices as multielement nozzles, ejectors, reflectors, and absorbers. The current state of knowledge regarding sonic boom control by configuration shaping and operational procedures is also summarized. Planned research in both areas of work is indicated where appropriate.

## JET NOISE ABATEMENT TECHNOLOGY

A variety of engine cycles can be considered for ST aircraft. However, the jet exhaust velocities for the cycles are considerably higher than those for CTOL aircraft. As a consequence, the jet noise for these engines, being a primary function of jet velocity, is much louder than for those used in CTOL aircraft. Although the fan for ST aircraft engines generally operates at low bypass ratios and high pressure ratios with resultant high noise, the unsuppressed jet due to its high velocity is the dominant noise source. There is, therefore, a need to suppress jet noise in order to render supersonic transport aircraft acceptable to the community. As the jet noise is suppressed the fan noise and core (internal) noise may become dominant, as in the case for CTOL aircraft. Noise attenuation means for these noise sources with ST aircraft are similar to those applied to CTOL aircraft.

## Variable Engine Cycles

The use of variable cycle engines has been proposed in order to help reduce jet noise. Some conceptual examples of these engines are shown in figure II-42. In figure II-42(a) a low-noise auxiliary fan augments the thrust of the main propulsion system, a duct-burning turbofan, at takeoff. Fan air from the main engine powers the auxiliary fan. The power extracted from the turbofan results in a low jet noise for the main engine also. After takeoff the auxiliary fan is not operated.

In the augmentor wing concept (see also section POWERED LIFT AIRCRAFT, p. 86) (fig. II-42(b)) bypass air from a turbofan is ducted through the wings at takeoff and ejected at high velocity into a two-dimensional (split-flap) ejector. Ambient air is entrained by the pumping action of the ejector and mixed with the fan bypass air. This results in a much lower jet velocity at the ejector exit plane and consequently the mixed flow noise level is much reduced. The mixing noise of the nozzle flow with the entrained air can be reduced significantly by suitable nozzle design (multielement nozzle) and by acoustically treating the inner surfaces of the ejector. In addition, some thrust augmentation due to the ejector also may be obtained. In the cruise mode the flaps are retracted. After takeoff, valves close off the air to the wing ducts and the turbofan is operated

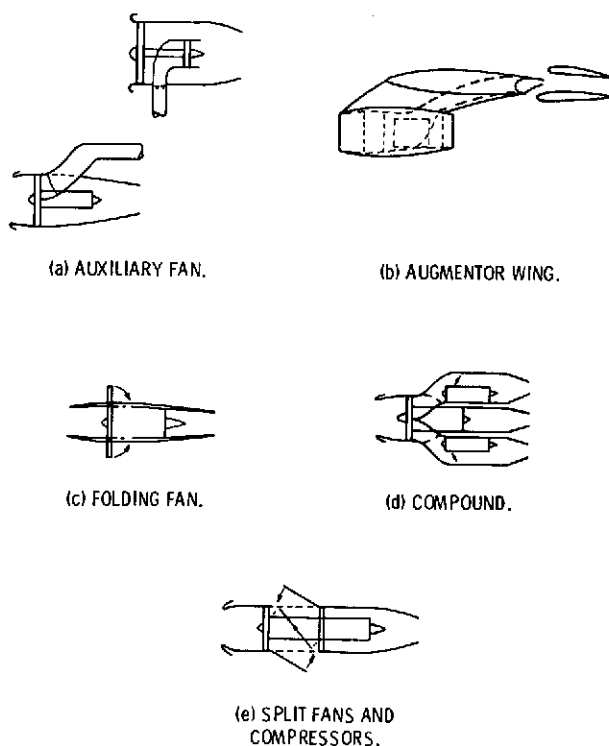


Figure II-42. - Variable cycle engine concepts.



in a conventional manner.

The folding-fan cycle of figure II-42(c) operates as a high-bypass-ratio turbofan at takeoff after which the fan blades are removed from the airstream by folding back and the engine operates as a conventional turbojet. The compound engine in figure II-42(d) comprises a central turbofan with satellite turbojets around the fan gas generator. At takeoff auxiliary inlets supply air to the auxiliary turbojets thus supplementing the thrust of the central turbofan. After takeoff the auxiliary inlets are closed and the turbojets use supercharged fan air. In this mode the engine performs similar to a conventional turbojet.

The split fan and compressor concept in figure II-42(e) uses auxiliary inlets and nozzles for the larger airflow at takeoff. As shown in this figure a separate fan is placed in front of and mechanically driven by a turbofan engine. At takeoff forward fan air is exhausted through auxiliary nozzles and the turbofan receives air from the auxiliary inlets. Thus a much larger airflow is taken on board with a smaller diameter engine. After takeoff the auxiliary inlets and nozzles are closed and the air from the forward fan goes through the turbofan and the engine operation is similar to a conventional turbofan engine.

From the description of these cycles it can be seen that these engines may be complicated and expensive. NASA has contracted with the General Electric Company and Pratt & Whitney to perform analyses of propulsion systems suitable for supersonic transport aircraft. A major goal of the work is to examine systems that can meet severe noise constraints, not only those of today but the possibly more stringent ones of the future. The engine contracts are coordinated with more general studies of the complete airplane design being performed by the Boeing, Lockheed, and Douglas airplane companies under contract to Langley Research Center. The Langley contracts will study the technology problems and design tradeoffs for the integrated airframe/engine combination, including such operational constraints as engine noise limits.

## Suppression Devices

At the high jet exhaust velocities of the more conventional engine cycles considered for a ST aircraft-type engine, the ability to meet acceptable community noise standards is difficult even with the best available jet noise suppressors. Suppression devices that approach present FAR-36 CTOL requirements have been under research; however, the associated aerodynamic performance losses and weight penalties severely compromise the economics of the propulsion and aircraft system. To achieve an environmentally and economically acceptable high-speed transport aircraft will require substantial improvement in jet noise suppression technology.

Although the approach used in developing jet noise suppressors has been largely empirical, a considerable volume of data has been amassed which is useful in providing guidance in planning new research and in stimulating the development of more general suppression concepts (refs. 18 to 23). The complex nozzle geometries used in noise suppressors (multitubes, chutes, spokes, etc.) lead to complex noise generation and/or reduction mechanisms.

The reduction of high velocity jet noise by means of current suppressor nozzle concepts requires the application of four basic techniques, which must be accomplished within a number of constraints. These constraints can be categorized as airplane performance (thrust, weight, drag, etc.) and design constraints (mechanical feasibility, installation, retractability, etc.) of the nozzle system. The four noise reduction techniques are as follows:

(1) Source energy modification. This requires using flow breakup and mixing in such a manner as to establish the desired jet-wake flow patterns to control the noise frequency spectrum, noise source location, and generated noise levels. Multielement nozzles are frequently used for this purpose. Some nozzles of this type tested by NASA are shown in figure II-43. In this approach the associated thrust, drag, and weight penalties must be considered.

(2) Redirection and control of energy generated. This can be accomplished by establishing favorable thermal profiles, additional fluid injection, and mechanical element arrangement. The objective is to direct the noise at low angles from the jet axis in order to maximize the length of the noise transmission path, thus taking advantage of atmospheric attenuation (item (4)). If most of the noise could be directed in this manner, ground noise levels would be greatly reduced.

(3) Energy absorption. Auxiliary devices such as acoustically lined ejectors, gas sheaths, or reflecting devices (wings, etc.) are used to absorb or intercept the noise once it has been radiated by the jet and prevent the noise from reaching the community. Redirection and control techniques are used to turn the sound toward the absorption device to take advantage of available attenuation.

(4) Atmospheric attenuation. The transmission of noise through the atmosphere is known to cause attenuation, particularly at the higher frequencies. The noise spectral characteristics can be shaped to take advantage of this effect. Each of these features must be accomplished while sustaining minimal thrust loss in both the takeoff and cruise modes. The suppression system will generally have to be retracted from the exhaust stream during cruise in order to meet performance and economic goals. In such cases, mechanical and thermal considerations with regard to the component structure become very important.

The use of multielement nozzles (tubes, chutes, spokes, etc.) for jet noise suppression dates back into the 1950 era. By use of such nozzles the total jet is divided into many smaller jets. Research by industry and government has led to an improved

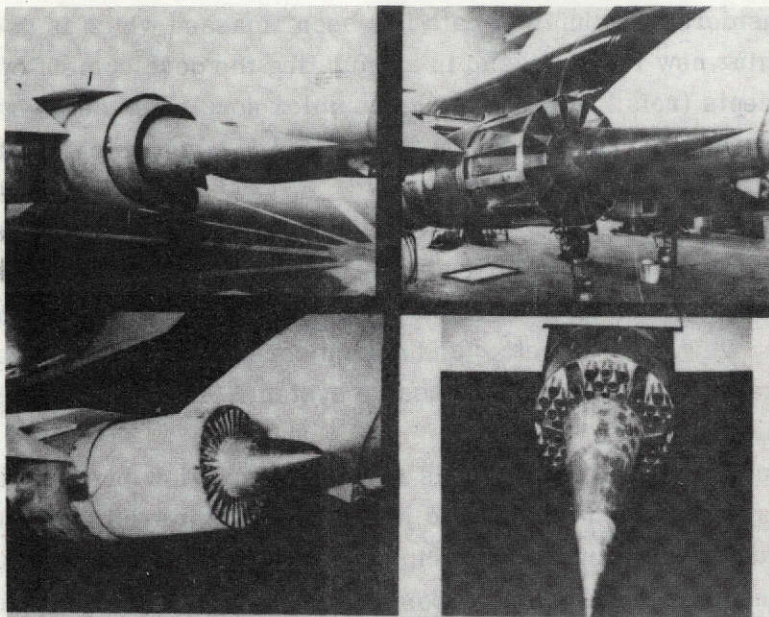


Figure II-43. - Typical noise suppression nozzles.

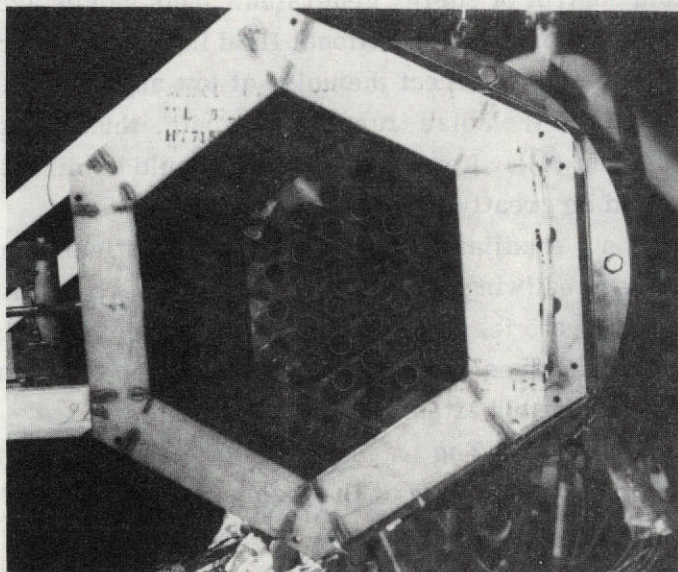


Figure II-44. - Experimental high velocity jet noise suppressor nozzle with ejector.

understanding of these devices. Such devices, however, are accompanied by thrust losses that vary with the particular configuration used. Severe material problems are encountered in placing a suppressor in a hot exhaust stream typical of afterburner operation.

A common type of experimental high-velocity jet noise suppressor is shown in figure II-44. It consists of a multitube or mixer nozzle combined with an ejector. Such a nozzle system can achieve significant noise reduction and is also potentially able to meet the operational constraints placed upon it. In this system, the multitubes are used to break up the exhaust flow into many, small jets. This shifts the noise-generation process to higher frequencies (fig. II-45) and somewhat lower levels. The reduced noise level at the lower frequencies are associated with the coalesced flow (mixed flow far downstream from the multitube exhaust plane) while the high frequency noise is associated with the small multitubes and occurs near the nozzle exhaust exit plane. If an acoustically lined ejector shroud surrounds the multitube noise generation region and is designed to absorb noise at the frequencies in this region, it is theoretically possible to reduce the noise to that generated by the lower velocity exhaust jet emerging from the ejector exit plane. This jet noise level is the minimum obtainable with the particular nozzle-ejector system. It should be noted that little of the low frequency noise is attenuated by the lined ejector since most of it is generated downstream of the ejector exit plane.

The ejector serves as a surface to which an acoustic liner can be attached as well as providing thrust augmentation during takeoff. In order to minimize performance losses in cruise, the ejector can be retracted and the mixer nozzle elements stored within the confines of the engine nacelle. Development of a variable-geometry ejector to minimize thrust losses for the various flight modes can also be considered.

A model and full-scale experimental program has been conducted by The Boeing Company for NASA to acquire a parametric set of acoustically lined ejector jet noise suppression data from which a design technology could be formulated. Some of the nozzle configurations tested are shown in figure II-46. Ground static tests were conducted using a J-75 turbojet engine with a 37-tube suppressor nozzle. Ejectors of two lengths, 1 and 2 shroud diameters, were tested with various linings. A total of 7 lined ejector configurations were evaluated at full scale over the engine operation range of 1.4 to 2.4 engine pressure ratio, corresponding to jet velocities of 1000 to 2000 ft/sec. Corresponding 1/4-scale models of 17 lined ejector configurations were tested over a range of nozzle pressure ratios of 1.4 to 4.0 and jet temperatures from ambient to 1500° F. For both full-scale and 1/4-scale tests a round convergent nozzle was tested to establish baseline acoustic data. The liners were designed using an existing procedure for fan-duct liners. For a given type of geometry, specified flow Mach number, and desired tuning frequency, corresponding to the frequency of the most annoying noise, the suppression was predicted as a function of lining-panel porosity, an example of which is

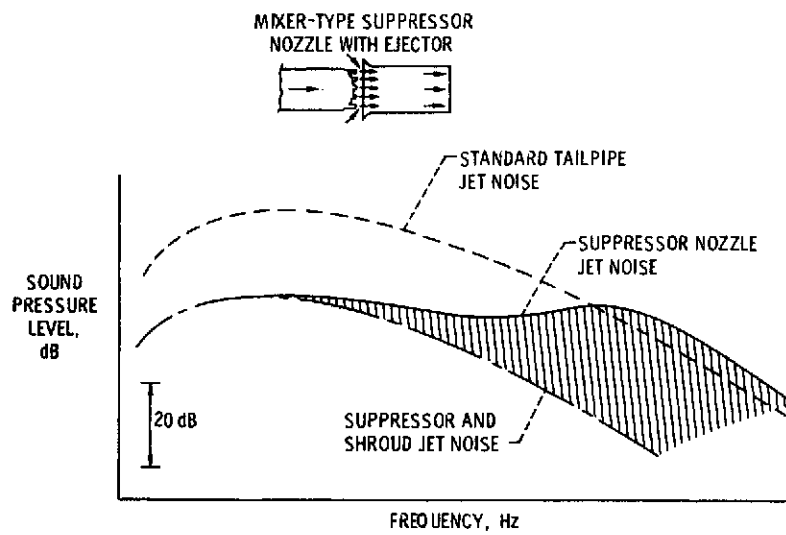


Figure II-45. - Jet noise suppression.

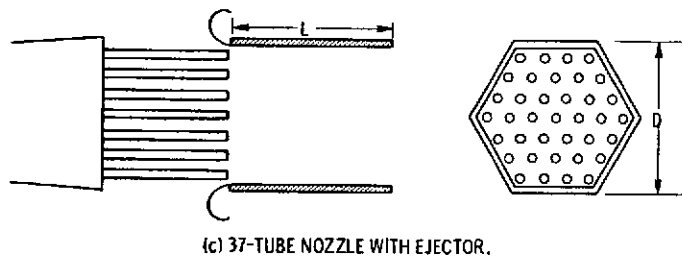
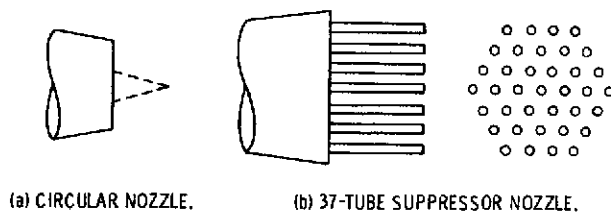


Figure II-46. - NASA-Boeing test configurations.

shown in figure II-47. From a family of such design curves, various linings were chosen to give maximum noise attenuation. A brief discussion of some of the major results of this study follows.

Figure II-48 shows typical sound spectra for the full-scale tests, at 200 ft from the nozzle and at an angle of  $140^\circ$  from the nozzle inlet, for various nozzle and ejector configurations having 10.6 percent open area panels with a 2.1-in. cell depth. The engine pressure ratio is 2.4, and the jet total temperature  $1000^\circ\text{F}$ . The upper curve is for the round convergent nozzle, showing the characteristic loud, low-frequency noise. The 37-tube suppressor nozzle shifts the peak noise to higher frequencies and produces some sound pressure level (SPL) reduction at all frequencies. Adding the 52-in. hard wall ejector gave little further noise reduction; in fact, refraction effects cause higher noise

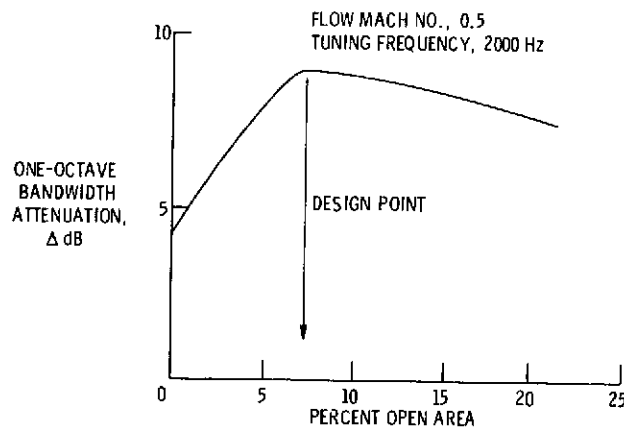


Figure II-47. - Predicted acoustic liner performance.

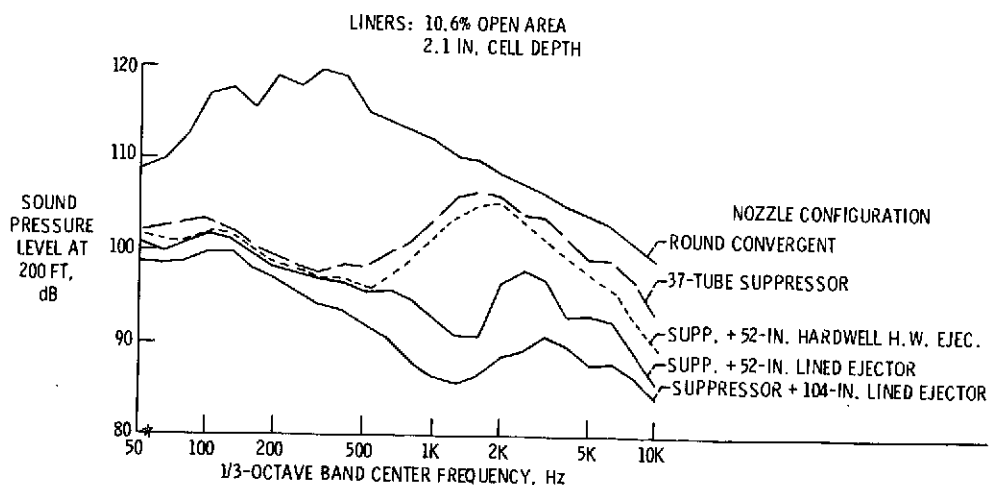


Figure II-48. - J-75 sound pressure level spectra. Angle measured from inlet,  $140^\circ$ ; engine pressure ratio, 2.4.



at some angles for the hard-wall ejector as compared to 37-tube nozzle alone. Adding the lining to the 52-in. ejector yielded a significant reduction in high-frequency noise, with essentially no attenuation at frequencies less than 500 Hz; however, a significant peak remained at a frequency of 2500 Hz, which is in a very annoying range. Doubling the length of the lined ejector provided still further significant reductions in high-frequency noise, with some low-frequency noise reduction also.

These reductions in SPL also yield reductions in the perceived noise level (PNL) as illustrated in figure II-49 for these same configurations. The reduction of maximum

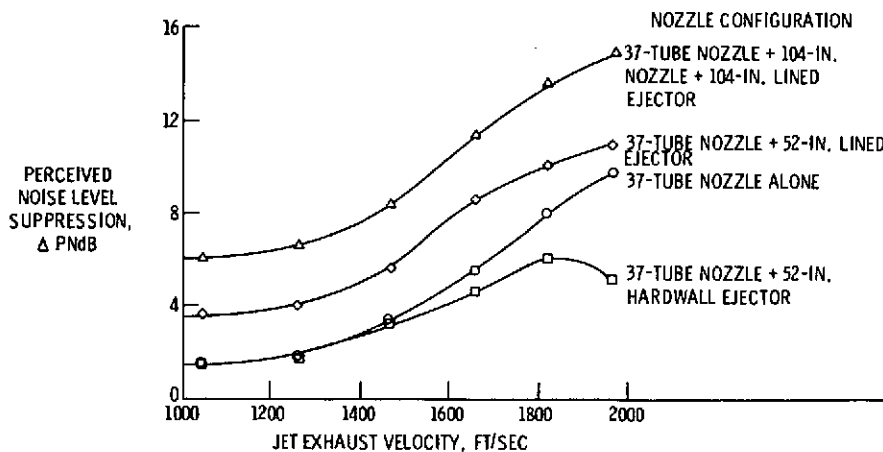


Figure II-49. - J-75 engine PNL suppression at 0.35 nautical mile sideline distance.

PNL below the maximum PNL for the circular nozzle is plotted against nozzle jet velocity. The attenuation generally increases with increasing velocity; this is typical of most suppression devices. The trends are similar to those shown in figure II-48 except for the hard-wall ejector, which gives less suppression than the 37-tube nozzle alone. This is due at least in part to refraction effects, which cause the sound to be directed away from the jet axis, thus reducing the path length over which atmospheric attenuation and spherical radiation can work to reduce the SPL. A maximum suppression of about 15 PNdB was obtained with the 104-in. lined ejector, while the 52-in. lined ejector gave a maximum suppression of about 11 PNdB.

Figure II-50 indicates that 1/4-scale and full-scale 37-tube nozzle data show good agreement in terms of SPL suppression as a function of frequency. The scale model data are shifted in frequency by a factor of 4, in agreement with theory. This indicates the validity of small-scale testing in evaluating suppressor nozzles.

A comparison of the predicted and measured noise attenuation obtained with the 52-in. acoustically lined ejector is shown in figure II-51 in which the sound power reduction is plotted as a function of frequency. While the prediction agrees relatively well with the

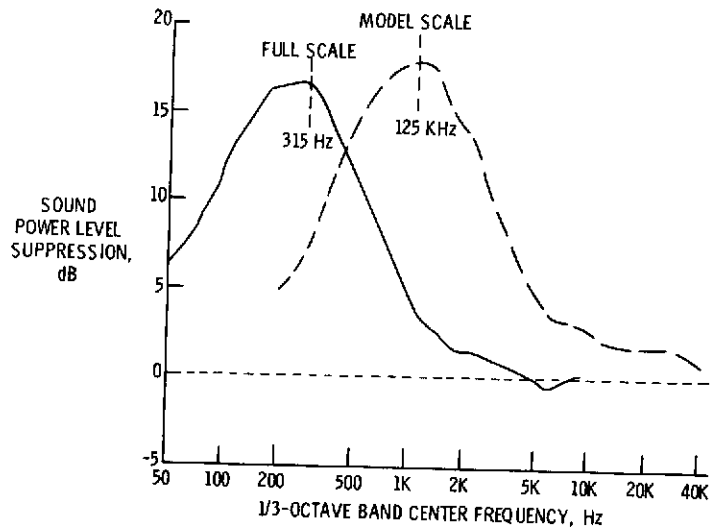


Figure II-50. - Sound power suppression obtained with 37-tube suppressor nozzles. Pressure ratio, 2.4; jet total temperature, 1000° F.

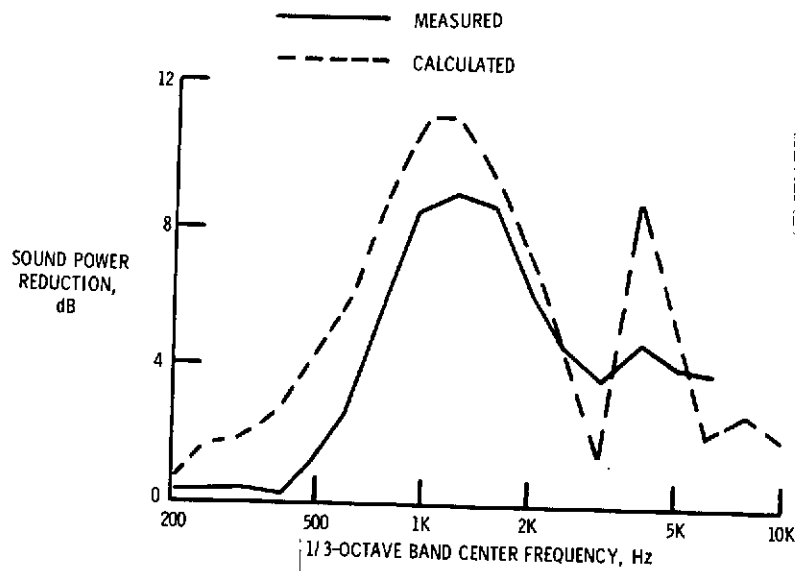


Figure II-51. - Comparison of measured and calculated noise attenuation for J-76 engine with 52-inch acoustically lined ejector. Pressure ratio, 2.4.



measured values, further improvements in the prediction procedure are needed to account for flow gradients and noise source locations.

The following conclusions were drawn from this liner ejector-suppressor technology study:

(1) Lined ejectors provided significant additional jet noise suppression above that provided by a multitube suppressor nozzle by as much as 6 dB.

(2) A maximum sideline perceived noise level reduction of 15 PNdB relative to the round nozzle was obtained with the 2-diameter long acoustically lined ejector.

(3) Further improvements in the acoustic-lining prediction procedure are needed to account for flow gradients and noise source locations.

Under static conditions the 37-tube suppressor nozzle has a constant 2-percent loss in thrust compared with the baseline conical nozzle over the entire pressure ratio range of the engine. With the ejector, the static thrust of the system was increased at least 8 percent over that of the conical nozzle. This increase in thrust was due in part to the large bellmouth used on the ejector; however, on the basis of other NASA tests with flight-type ejectors (unpublished data), this level of static thrust augmentation also appears reasonable with flight-type hardware.

NASA is also conducting research on novel jet noise suppressors. Shown in figure II-52 is a nozzle design that shows some promise for noise reduction at supersonic exhaust conditions. The nozzle is a convergent-divergent nozzle that operates in an over-expanded condition (ref. 24). The design of the nozzle is such that the jet is divided into lobes. An ejector is placed around the nozzle. The convergent portion is a standard conical nozzle. The divergent portion consist of eight plates separated by V-gutters. A

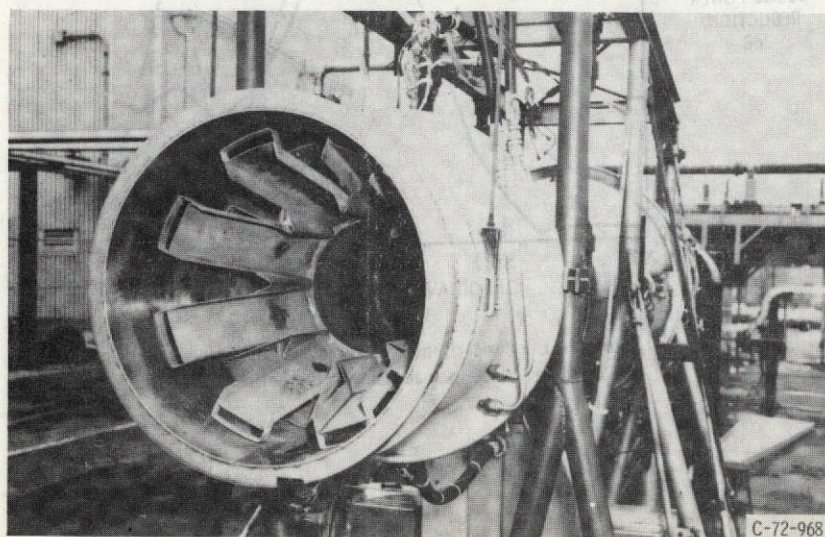


Figure II-52. - Divergent lobed suppressor nozzle on J-85 afterburner test rig.

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step area increase exists at the nozzle throat. A low pressure exists in the base cavity formed by this area step. This low pressure causes the flow to overexpand. The flow attaches to the plates and is divided among the plates by the V-gutters. A strong shock structure results, and the jet velocity rapidly decreases.

Some of these effects can be seen in figure II-53, which shows the axial Mach number distribution along the jet centerline and along the plates. The Mach number is higher along the plate region, which indicates that the flow has expanded into this region and, in fact, is even concentrated in this region. Shocks exist just upstream of the end of the

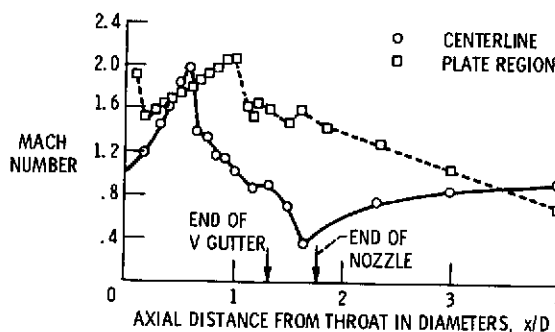


Figure II-53. - Mach number distribution along primary plate and nozzle centerline.

V-gutters. Downstream of these shocks, the Mach number decreases and the flow becomes subsonic in about 3 or 4 diameters, and the normally long supersonic mixing region has been eliminated.

The particular nozzle tested was optimized for supersonic exhaust conditions, and no noise reduction was obtained at subsonic velocities. At a typical cold flow operating point for the nozzle with a hard-wall ejector and at a pressure ratio of 3.5, a 14-dB noise reduction in peak noise level and no static thrust loss compared with a conical nozzle was obtained. Use of a lined ejector should yield a further 5 to 6 dB reduction in noise.

A summary of the current state of the art in supersonic jet noise suppression through the use of multielement nozzles is shown in figure II-54, in which the amount of noise suppression is plotted as a function of static thrust loss. The plot is based on a pressure ratio of 3.0 across the nozzle exhaust plane and a jet total temperature of 1000° to 2000° F. A reference line is also shown that illustrates the small amount of noise suppression achievable by throttling back an engine in order to operate at thrust.

The shaded regions identified in figure II-54 represent a large mass of data and indicate that significant strides have been made in achieving suppression nozzles that have high noise suppression and low thrust losses. Recent static tests with an advanced con-

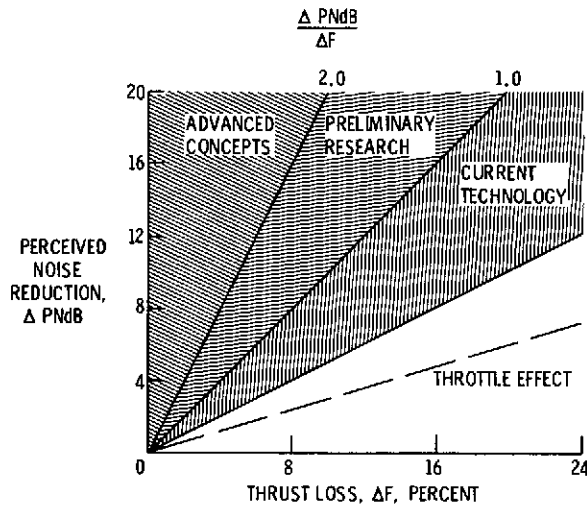


Figure II-54. - Current suppressor noise reduction effectiveness. Pressure ratio, 3; jet total temperature range, 1000° to 2000° F.

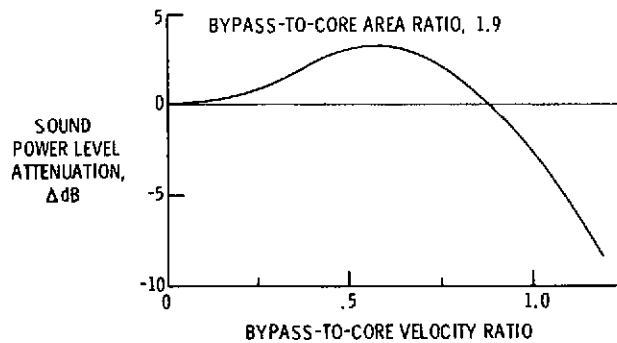


Figure II-55. - Jet noise attenuation with bypass flow (coaxial flow nozzle).

cept suppressor utilizing a 61-tube stowable nozzle with an acoustically lined ejector and shield showed an overall sideline noise suppression capability at 0.35 n. mi. of 20 dB with a thrust loss of 5 percent at a jet velocity of 2500 ft/sec (ref. 25). This suppressor utilized integrated disciplines of mechanical systems, propulsion, and noise.

Since some candidate cycles for a ST propulsion system would produce two exhaust streams, the noise generation in coaxial (bypass-type) nozzles becomes an important problem area. Use of subsonic coaxial nozzles has resulted in noise reduction as shown in figure II-55 (ref. 26). With supersonic exhaust jets (cold flow), still further noise reductions have been reported due to changes in shock-wave patterns (ref. 27). Refraction effects due to temperature differences between the streams may significantly alter the noise directivity. This phenomenon is similar to that observed when the outer flow

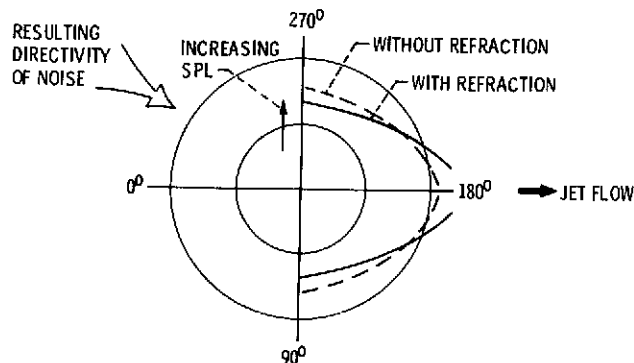
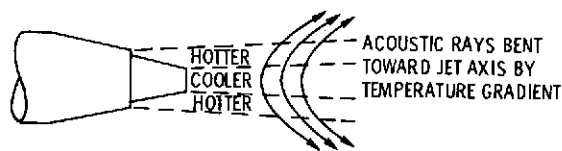


Figure II-56. - Refraction of jet noise by hot bypass flow.

stream has a higher speed of sound than the core flow (i. e., helium shield). It has been suggested that a relatively hot low velocity annular flow as would be generated by a duct burning engine might bring about sideline and flyover noise reduction by bending the sound rays in toward the jet axis as illustrated in figure II-56. To investigate this phenomenon Lewis is modifying an existing cold-flow, coaxial nozzle facility so that either or both streams can be heated to 1600° F at nozzle pressure ratios up to 3 (jet velocities up to about 2500 ft/sec). In addition, it is planned to study contractually noise suppression means for the bypass flow nozzles. This work will consist of an experimental program in which the pertinent flow and geometry variables will be studied parametrically.

#### In-Flight Effects on Suppression Devices

So far this discussion has centered on static test results obtained with various suppressor nozzles, both aerodynamically (thrust) and acoustically. The question arises as to how the aircraft forward speed influences the noise suppression characteristics of the various nozzle configurations.

While the understanding of noise generating mechanisms and static suppression techniques have been advanced by research, little effort has yet been expended to develop suppressed jet technology for the final flight application. Test programs are needed to develop data to aid in understanding flight velocity effects and to be more cognizant of their implications in flight noise predictions. This becomes particularly important



since noise regulations are based on the subjective response rating of effective perceived noise level (EPNL), which is a function not only of peak noise but also its tone content and time duration. Thus, an understanding of flight velocity effects on the directivity of unsuppressed and suppressed noise as well as on the peak noise is required.

NASA and General Electric, under contract to NASA, have performed flight noise tests of several suppressed and unsuppressed nozzles installed on a modified F-106B aircraft. The aircraft is equipped with two auxiliary J85-13 engines, one mounted under each wing (fig. II-57). Only one auxiliary engine at a time is used for the noise tests.

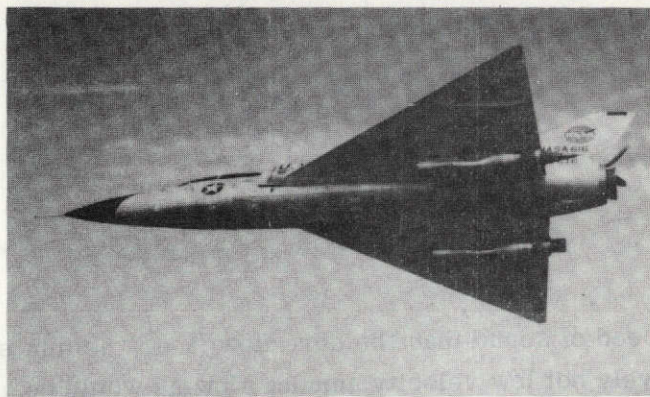


Figure II-57. - NASA flight jet noise research with F-106B aircraft and J-85 engines.

Some of the nozzles tested were shown in figure II-43. General trends of flight velocity influence applicable to all nozzles have not been observed, indicating the need for further study (refs. 28 and 29).

In order to improve the understanding of forward velocity effects, NASA is conducting a comparative evaluation of the effect of forward velocity on the noise characteristics of supersonic-aircraft-type suppressor nozzles both in flight (Lewis Research Center) and in a 40- by 80-foot wind tunnel (Ames Research Center). A calibrated J85-13 engine will be installed in the wind tunnel for tests with various nozzles that have already been flight tested by Lewis. These nozzles will include a 104-elliptical-tube suppressor nozzle (fig. II-58) with and without an acoustically lined shroud. Installation of the engine pod, including the nacelle and inlet, will be as nearly identical as practical for the two programs. Some differences will necessarily exist; for example, the flight Mach number range is approximately 0.33 to 0.40, while the wind tunnel Mach number range is from 0 to 0.30 or less, depending on model drag. Furthermore, for the flight tests, the nozzle is in motion with respect to the microphones, and for the wind tunnel tests, it is not. The comparative evaluation of flyover noise levels will be made for jet velocities



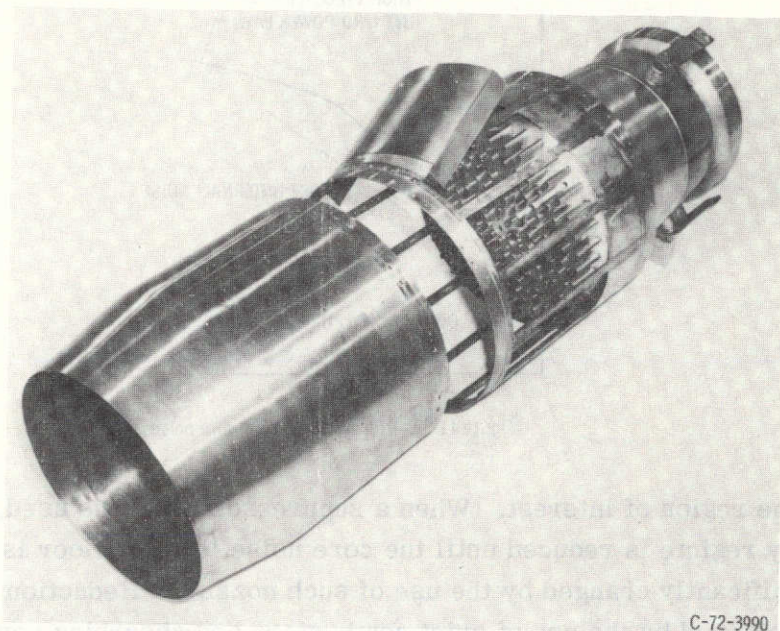


Figure II-58. - 104-tube suppressor nozzle with ejector used for in-flight F-106B noise program.

ranging approximately from 1100 to 2100 ft/sec.

The capability of making wind tunnel and flight noise measurements will be further developed and the limitations of each method will be documented. Using these two experimental techniques, a comparative evaluation of the effects of forward velocity on the noise characteristics of supersonic-transport-type suppressor nozzles will be made. If the experiments prove sufficiently accurate, the differences in source motion may allow some investigation of source motion effects on noise spectra.

#### Core Noise

The problem of CTOL and STOL core noise was discussed previously. It was shown that at low jet velocities associated with CTOL core (internal) noise attributed to combustion, turbine and flow wakes from structural protrusions (struts, etc.) emerged as the dominant noise source. At supersonic jet velocities, however, core noise is a secondary factor when compared to the unsuppressed jet noise. However, when suppressor nozzles are used, core noise emerges as a floor to jet noise reduction.

A simple sketch is shown in figure II-59 in which pure jet noise and core (internal) noise are related to jet velocities. At the lower velocities, pure jet noise obeys an 8-power relationship with jet exhaust velocity while at high jet velocities, a 3-power relationship is observed. Core noise appears to follow a dipole or 6-power relationship with

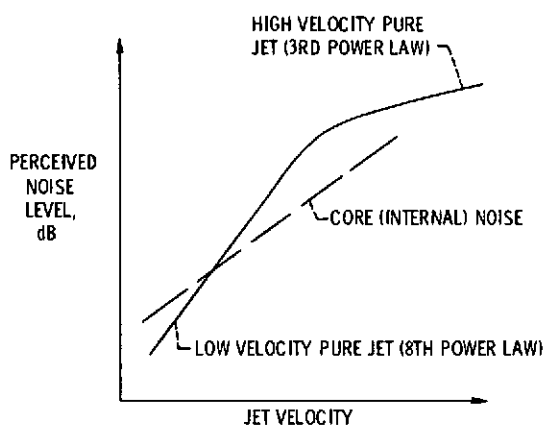


Figure II-59. - Relation of jet and core noise.

jet velocity in the region of interest. When a suppressor nozzle is used, the jet noise in the high-velocity regime is reduced until the core noise level or floor is reached. Core noise is not significantly changed by the use of such nozzles. Reduction of the core noise floor could be achieved by the use of quiet combustors and absorbing some of the remaining internal noise by acoustic liners. A reduction of the internal noise floor is difficult to achieve solely with liners because the core noise, particularly combustion noise, is dominated by low-frequency noise. This latter noise is difficult to remove with reasonably sized lightweight acoustic liners.

## SONIC BOOM

The sonic boom, which is associated with the shock wave patterns of an aircraft, is of concern only during the phases of the flight which are accomplished at speeds exceeding the local speed of sound. The nature of the sonic boom ground exposure patterns are shown in figure II-60. Shown schematically in the figure is an airplane flight track extending from subsonic to supersonic speeds. Beneath the flight track are shown sketches of the shock-wave impingement patterns and the associated distributions of N-wave pressures, both along the track and perpendicular to it. In references 30 and 31, information is presented regarding the state of knowledge of the sonic-boom phenomena dealing with the ontrack and lateral ground exposures during steady flight for quiescent atmosphere conditions, the effects of atmospheric dynamics on bringing about sonic-boom-signature variations, and the pressure buildups resulting from accelerated flight.

The significant factors which affect the sonic boom include airplane design, which involves weight, size, and volume and lift distributions; airplane operations, which involve altitude, Mach number, and flight path; and the atmosphere, which involves pres-

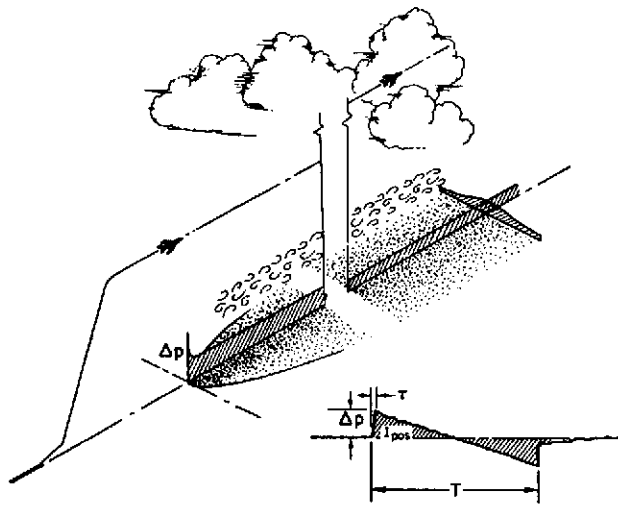


Figure 11-60.- Sonic-boom ground-pressure patterns.

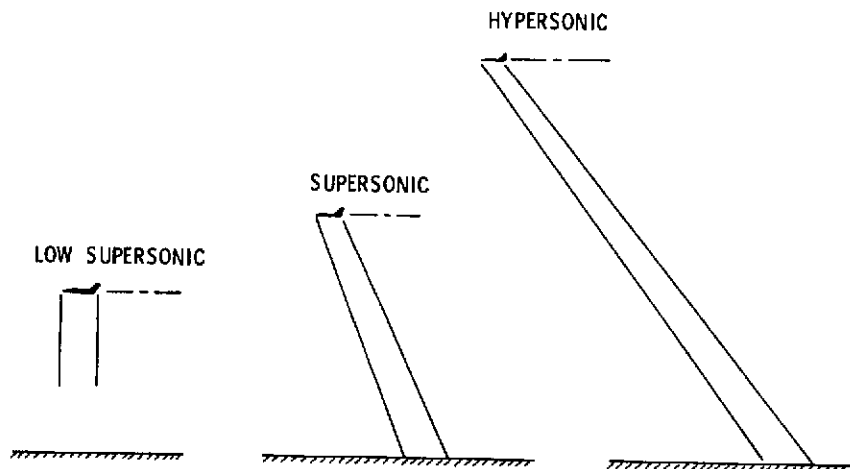


Figure 11-61.- Schematic of shock waves associated with three operating regimes.



sure, temperature, and wind gradients and turbulence. Discussions of the effects of each of these factors as they relate to transonic, supersonic, and hypersonic operating regimes shown in figure II-61 are presented.

### Sonic-Boom Exposures For Steady Flight and a Steady Atmosphere

Shown in figure II-62 are the ontrack sonic-boom overpressures (associated with the N-wave shape signature shown in the sketch) as a function of airplane altitude for a number of airplanes including a fighter, a bomber, a supersonic transport, and a hypersonic transport. The experimental points obtained from overflights of the Lockheed F-104, Convair B-58, and North American XB-70 airplanes (ref. 32) represent averages of a large number of measurements. The shaded areas represent the predicted and estimated nominal values based on current theory, a standard atmosphere with no wind being assumed. The results given in figure II-62 indicate that the overpressure decreases with increasing altitude and with decreasing airplane size. Good agreement exists between theory and experiment for a wide range of airplanes and operating conditions. The estimated levels for the hypersonic airplane are justified on the basis of recent measurements on Apollo 15, 16, and 17 launch and reentry vehicles. Results indicate that satisfactory agreement exists between calculations and the measured boom data

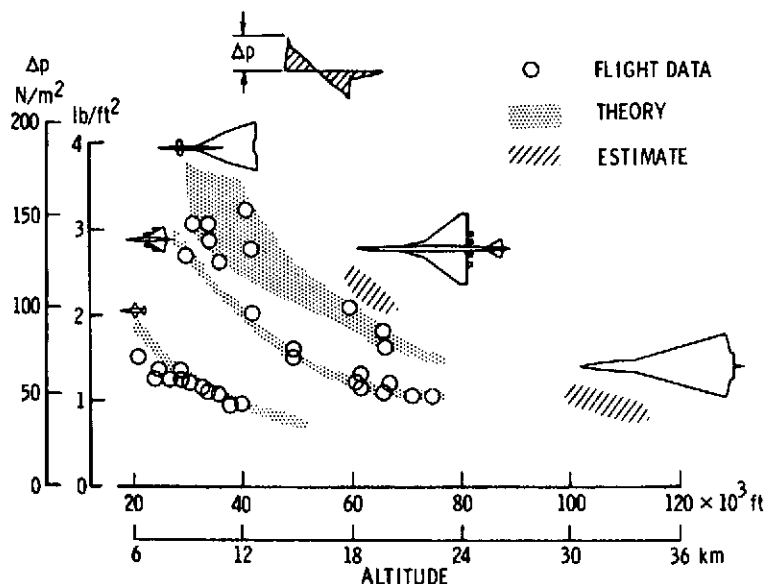


Figure II-62.- Sonic-boom overpressure characteristics of various supersonic airplanes as a function of altitude.

from the spacecraft at Mach numbers in excess of 10 and at altitudes in excess of 70 kilometers (km). Thus, existing methods involving empirical inputs from wind tunnels may be useful for predicting sonic boom exposures for very high Mach number and altitude conditions of future hypersonic transports (see ref. 33).

The data in figure II-63 relate to lateral-spread measurements from the XB-70 airplane at two altitudes and two Mach numbers (see ref. 32). The sonic-boom overpressures are shown as functions of lateral distance to either side of the airplane ground track. The data symbols represent the average of measurements from a large number

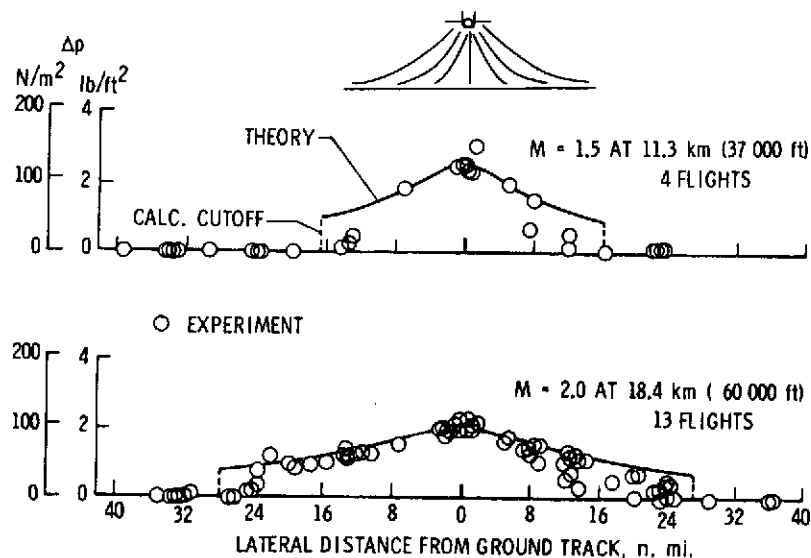


Figure II-63.- Sonic-boom overpressures for the XB-70 airplane as a function of lateral distances for two different flight conditions.

of microphones for 4 flights and 13 flights of the XB-70 at 11.3 km (37 000 ft) and 18.4 km (60 000 ft), respectively. Also shown in the figure are the calculated curves and lateral "cutoff" distances with current theory being used and a standard atmosphere with no wind being assumed. Again good agreement is noted to exist between theory and experiment. In addition, both theory and experiment show that the boom overpressures are highest on the ground track and decrease with increasing lateral distance, until the shock waves are refracted at the lateral cutoff (see ref. 34).

Comparisons of the calculated and measured lateral extent of the sonic-boom patterns as a function of airplane altitude and Mach number for steady flight in a standard atmosphere are given in figure II-64. The data points represent averages of a number of measurements involving various airplanes. The widths of the sonic-boom patterns on the ground increase with increasing altitude and Mach number. For example, at an alti-

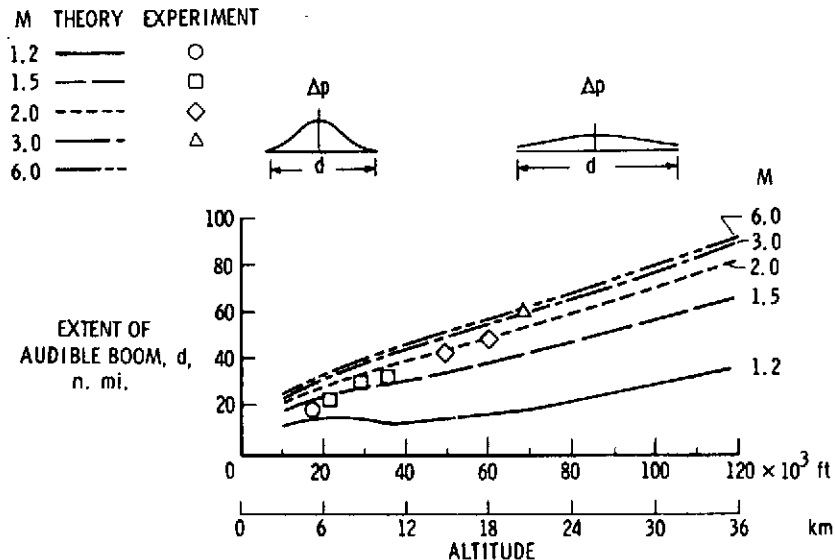


Figure II-64.- Width of audible sonic boom on the ground.

tude of 6.1 km (20 000 ft) and  $M = 1.5$  the total width of the pattern is 20 n. mi.. At 18.4 km (60 000 ft) and  $M = 2.0$  the pattern width is about 60 n. mi.. However, as is illustrated by the two sketches at the top of the figure, supersonic flights at low altitude result in narrow width patterns having higher overpressures, whereas at higher altitudes the pattern widths are much broader but with lower ground overpressures. Good agreement is noted between measured and calculated values. The hypersonic airplanes will operate at altitudes and Mach numbers beyond the current experience. However, there is no reason to believe that theory would not provide reasonable estimates of the pattern width for this flight regime.

### Sonic Boom Minimization

The discussions thus far have related to the nominal ontrack and lateral sonic-boom pressure distributions, and it has been shown that sonic-boom effects are minimized through increased distance between the airplane and the ground. Minimizing the sonic booms through airplane design modifications have also been investigated (refs. 34 and 35). The basic approaches that have been considered are illustrated in the sketches of figure II-65. Sonic-boom minimization can be achieved through a reduction in the overpressure or an increase in the signature rise time, each of these parameters being significant with regard to human and structural response (ref. 36). As illustrated in the

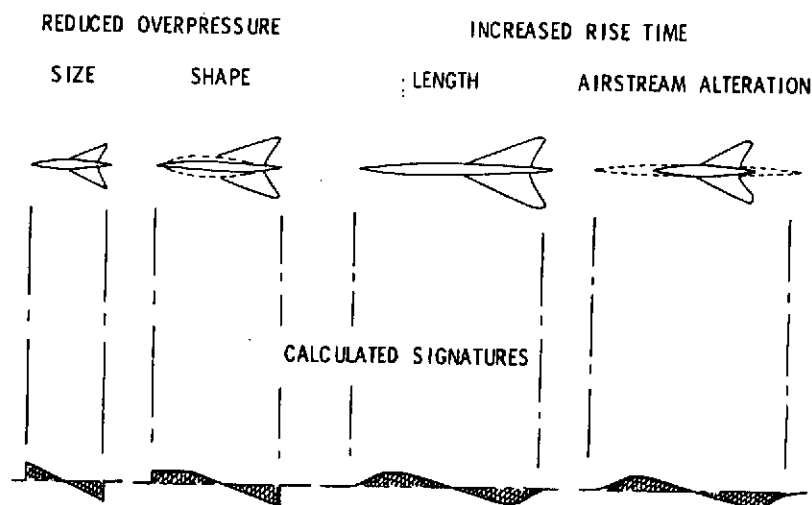


Figure II-65.- Illustrations of various concepts employed for obtaining sonic-boom minimization.

sketches on the left of figure II-65, reduced overpressures can be obtained by reducing the size of the airplane (i. e., low airplane weights) or by proper shaping of the airplane geometry to provide a modified signature (a flat top signature). These two approaches have been given much consideration in the past, and reduction in bow-wave overpressures of the order of about 30 percent seems obtainable.

More recent minimization techniques involving increasing rise times have been investigated (ref. 37). If the rise time of the signature could be increased to the point where a sine wave would result instead of an N-wave, the sine-wave pressure signature would not be audible to an outdoor observer although building responses would still result. In order to obtain finite rise times of the order of 10 to 15 milliseconds (msec), the airplane length would have to be increased by at least a factor of 3 (to about 310 m (1000 ft)) over the greatest length now being considered. Another means would be to alter the airstream so that the same effects associated with the increased length are obtained. This could be accomplished by the addition of heat or other forms of energy. Recent studies (refs. 34 and 37) regarding the airstream alteration or "phantom body" concept suggest that large amounts of heat or energy are required (at least the equivalent of the output from four more propulsion engines) to obtain finite rise-time signatures. The performance penalties associated with the previous approaches and their overall feasibility remain to be evaluated.

## Effects of the Atmosphere

The effect of the atmosphere on sonic-boom propagation is to cause variations in the measured signatures as illustrated by the data of figure II-66 (see ref. 38). The variations in the bow-wave overpressures as measured along the instrumented linear array of 2438 m (8000 ft) are shown for an airplane in steady level flight. The line represents the nominal overpressure calculated for a standard atmosphere with no wind. Overpressure variation along the ground track is cyclic in nature. The high overpressures are usually

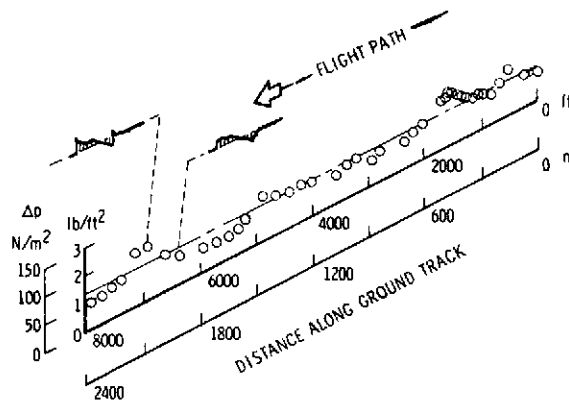


Figure II-66. - Sonic-boom overpressures as a function of distance along the ground track for a fighter airplane in steady flight at a Mach number of 1.3 and an altitude of 9.3 km (30 500 ft) along with sample signatures.

associated with peaked signatures, whereas the lower pressures are associated with rounded signatures. These signature distortions are attributed to the lower layers of the atmosphere. The phenomena are thus statistical in nature, and they occur either as a function of time or distance.

A summary of the variations of the ontrack overpressures for steady level flight resulting from the atmosphere is given in figure II-67. This statistical analysis comprises most of the planned sonic-boom experiments that have been conducted in this country. Data are included for a wide range of airplanes, a Mach number range from 1.2 to 3.0, and an altitude range from 3.04 km (10 000 ft) to above 21.4 km (70 000 ft). A total of 12 406 data samples have resulted from 1625 supersonic flights. Although the number of data samples would be considered small from a statistical standpoint, they are large from a logistics standpoint.

Plotted in figure II-67 is a relative cumulative frequency distribution and histogram for ontrack measurements showing the probability of equaling or exceeding the ratio of

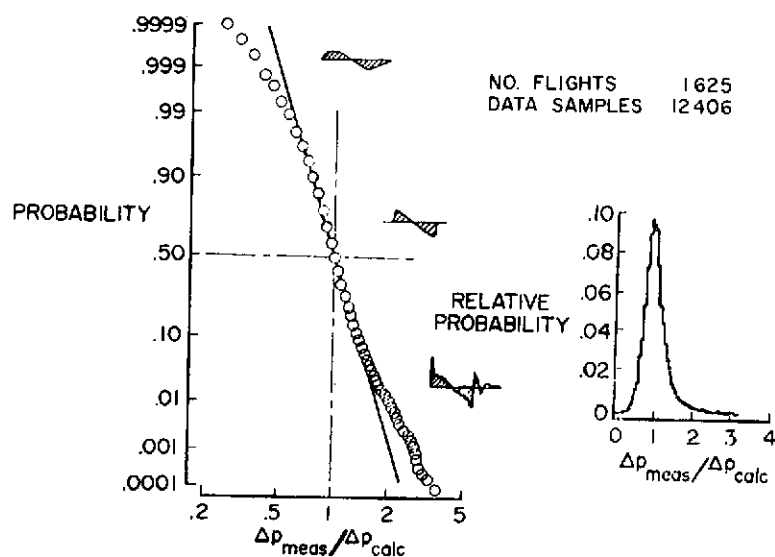


Figure II-67. - Probability of exceeding given values of measured to calculated sonic-boom ground overpressures along the airplane flight track.

the measured overpressure to the calculated or nominal overpressure for steady flight in a standard atmosphere. For this type of presentation, all the data would fall in a straight line if the logarithm of the data fitted a normal distribution. Rounded signatures of the wave form shown in the figure are usually associated with overpressure ratios less than 1. Nominal or N-wave signatures are observed on the average, and peaked signatures of higher overpressures are observed usually at ratios greater than 1. The data of figure II-67 indicate that variation in the sonic-boom signatures as a result of the effects of the atmosphere can be expected during routine operations.

### Effects of Airplane Maneuvers

Sonic-boom enhancement can result from various airplane maneuvers (ref. 32). In figure II-68 are illustrated three types of maneuvers which could result in pressure buildups at ground level (a longitudinal acceleration, a 90° turn, and a pushover maneuver). In each maneuver, pressure buildups occur in the localized regions suggested by the shaded areas shown in the sketches of figure II-68. It should be pointed out that although the airplane and shock waves are moving, the areas on the ground in which pressure buildups occur are fixed and do not move with the airplane. The pressure buildups in these focus areas are a function of the type of maneuver and acceleration involved. Operationally, pressure buildups will always result for the longitudinal maneuver when

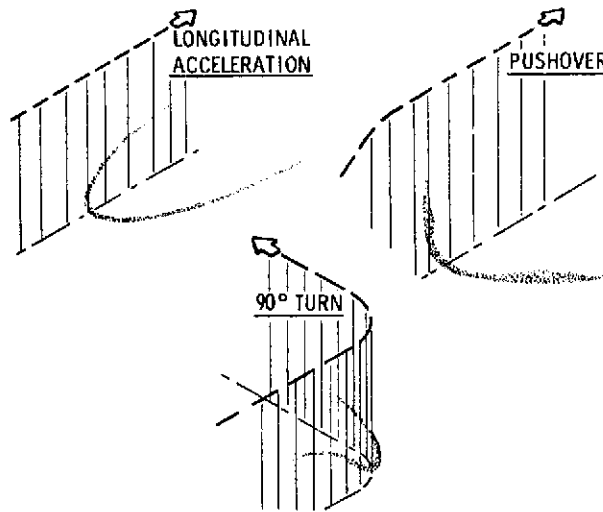


Figure II-68. - Areas on the ground exposed to focused sonic booms resulting from three different airplane maneuvers.

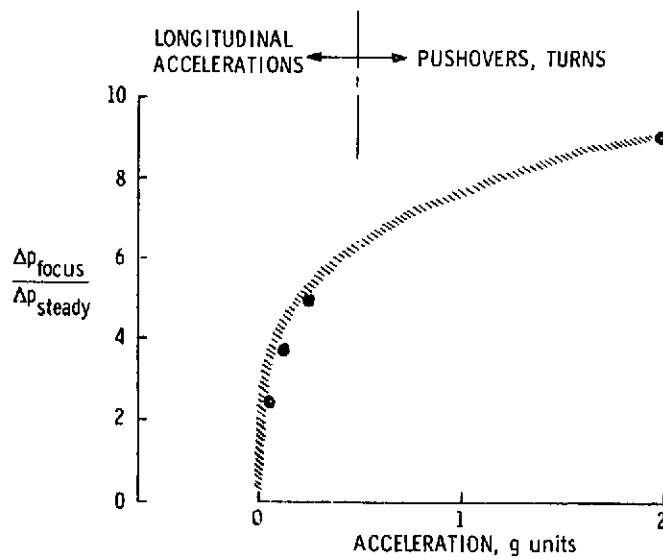


Figure II-69. - Effect of airplane acceleration on sonic-boom overpressure buildups in maneuvering flight.

the airplane accelerates from subsonic to supersonic speeds. The effects can be minimized by reducing acceleration rates. The pressure buildup areas associated with turns and pushover maneuvers can be minimized or avoided by reducing acceleration or by simply avoiding the maneuver.

The overpressure buildups, or focus factors, in these maneuvers are shown as a function of airplane acceleration in figure II-69. The information contained in this figure is a result of flight experiments conducted in this country (refs. 32 and 39) and in France (refs. 40 to 42). The data points shown represent the highest levels measured thus far for longitudinal accelerations and turning maneuvers. The hatched boundary, therefore, would represent the current upper bound. At the lower values of acceleration, which are usually associated with longitudinal accelerations, the overpressure in the focus is of the order of about 2 to 5 times the nominal overpressure for steady level flight at the same altitude and Mach number. For a turn maneuver involving a 2 g acceleration, a focus factor of up to 9 has been measured.

### Low Supersonic Operations

The discussions thus far have been concerned with airplane operations in which the shock waves extend to the ground and are reflected from the ground as illustrated in the upper right sketch of figure II-70. Now consider low supersonic operations where the shock waves extend down toward but do not intersect the ground, as suggested by the sketch in the upper left of the figure. The range of Mach numbers and altitudes over which cutoff Mach number operations can be performed is shown in figure II-70, with steady level flight in a standard atmosphere with no wind being assumed (see ref. 43). Flights at Mach numbers to the left of the hatched curve will result in no booms reaching the ground, whereas flights at Mach numbers to the right of the curve will result in booms reaching the ground. In figure II-70, the highest speed at which the airplane could operate in a standard atmosphere without producing booms at the ground is about  $M = 1.15$ . In the real atmosphere, variations in sound speed gradient do exist because of temperature and winds. For example, headwinds at altitude and higher temperatures at the surface would increase  $M_{\text{cutoff}}$ ; conversely, tailwinds at altitude and colder temperatures at the surface would decrease  $M_{\text{cutoff}}$ . The practical range of  $M_{\text{cutoff}}$  for a fairly wide range of atmosphere (ref. 44) is shown to vary from about 1.0 to about 1.3.

A description of the cutoff phenomenon may be obtained by examining the ray-shock diagram shown in figure II-71. The top sketch relates to the operating conditions in which the airplane velocity over the ground  $V_g$  is greater than the sound speed at the ground  $a_g$ . The airplane is shown moving in a direction from right to left and, for simplicity, only the bow wave is shown. The shock wave extends to the ground and is reflected upward. As the disturbances that form this shock wave are emitted from the



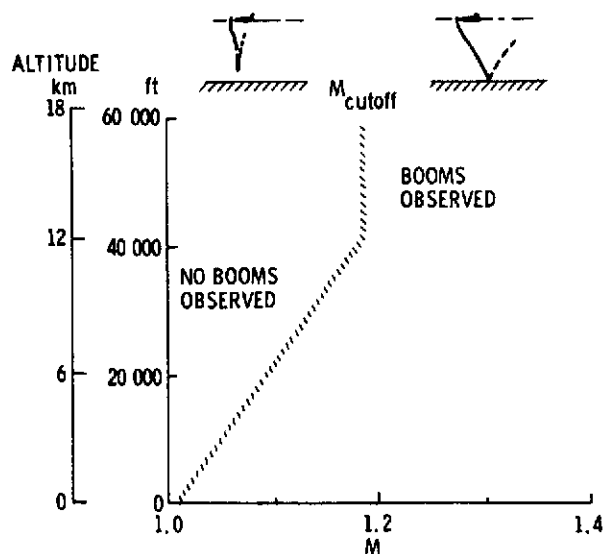


Figure II-70.- Combinations of airplane Mach number and altitude for complete sonic-boom cutoff for steady level flight in a standard atmosphere with no wind.

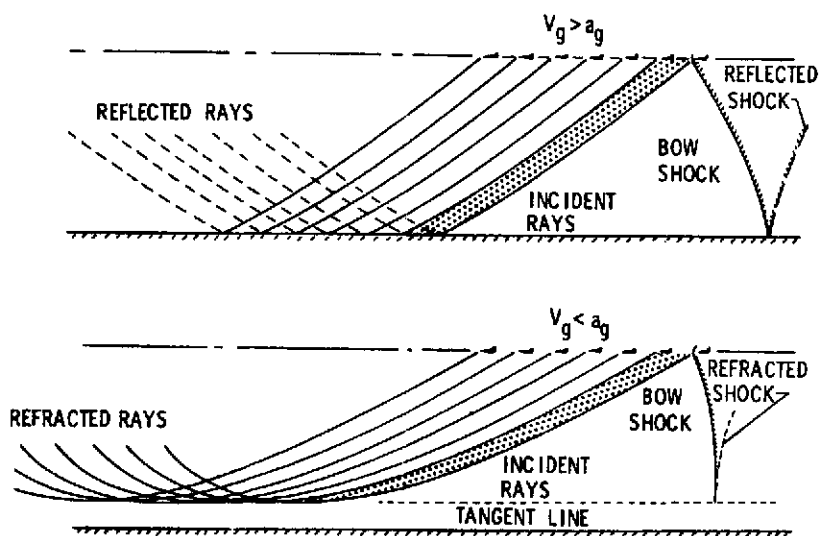


Figure II-71.- Ray-shock diagram for airplane operating at Mach numbers above and below the sonic-boom cutoff Mach number.

airplane, they travel toward the ground along ray paths indicated by the solid lines. These rays intersect the ground and are reflected upward, as illustrated by the dashed lines. Any number of such rays can be drawn from the airplane at different times along the flight path. Two consecutive rays are essentially parallel and tend to converge only slightly as they approach the ground.

The bottom sketch of figure II-71 relates to the conditions when the airplane speed over the ground  $V_g$  is less than the sound speed at the ground  $a_g$ . These conditions would be associated with an airplane flying below the cutoff Mach number. The rays have a greater curvature than those for the higher airplane speed and are totally re-refracted at an altitude above the ground. The rays, which have been drawn for various positions of the airplane along the flight track, become tangent to each other at the cutoff altitude. The areas between adjacent rays, as indicated by the shaded region, decrease until they theoretically approach zero where the rays become tangent. The pressures are expected to markedly increase in the regions where the area between the rays is decreasing. Thus, a caustic, or line focus, is formed where the rays become tangent at the cutoff altitude.

Recent experiments have been made to define the pressure field associated with the shock-wave extremities for flights at low supersonic Mach numbers (ref. 34). The results shown in figure II-72 are indicative of the sonic-boom phenomenon associated with flights at cutoff Mach number. The experiments used a 457-m-high (1500-ft) tower with microphones placed at 30-m (100-ft) intervals along the tower and also along the ground

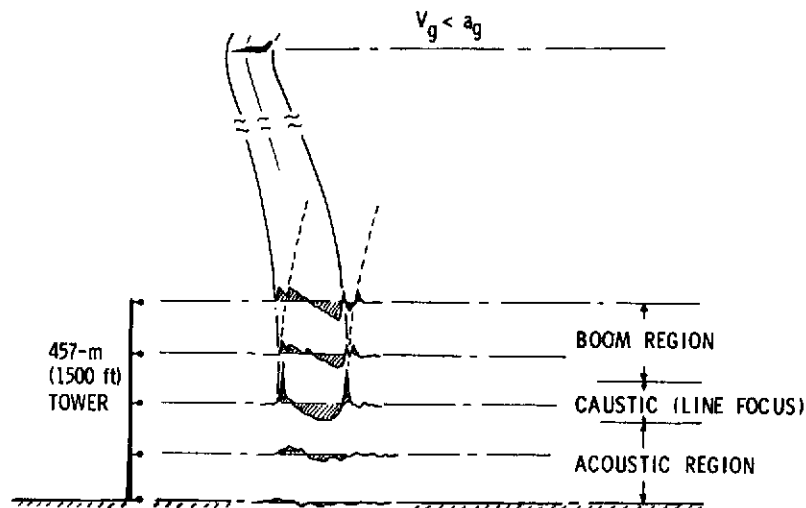


Figure II-72.- Measured sonic-boom signatures at various heights above the ground for an F-104 in steady level flight at cutoff Mach number. Altitude, 10.26 km (33 700 ft);  $M = 1.095$ .

(see ref. 45). The airplane was flown so that the shock patterns terminated within the tower heights. The solid lines represent shock waves, and the dashed lines represent the refracted waves. Also shown in the figure are the measured sonic-boom signatures that were observed as the shock-wave system moved across the microphones on the tower. In this particular experiment, the shock extremity was positioned so that pressure disturbances in the supersonic, sonic, and acoustic regions were measured. At the top of the tower, a normal N-wave sonic-boom signature was measured that included the incident bow and tail shocks and their refractions. At midtower, which was the approximate location of the shock extremity, a U-shape (caustic) signature was measured for which the amplitudes were larger than those associated with the N-wave signatures observed in the supersonic flow region. Near the base of the tower, below the shock extremity, the signatures are rounded or sinusoidal in shape and suggest acoustic disturbances.

The bow overpressure from signatures such as those shown in figure II-72 for the flight operations near cutoff Mach number are presented in figure II-73. The measurements, which represent the average values obtained from the ground and tower microphones, are from steady level flights of the F-104 airplane at 10.26 km (33 700 ft). The solid curve represents the overpressure variations suggested by theory, and the data points represent the measurements. Because  $M_{\text{cutoff}}$  varied somewhat (from about  $M = 1.09$  to  $1.12$ ) from flight to flight and over the 3-day test period because of variations in atmospheric conditions, the measured data have been normalized so that the overpressures associated with the caustic or U-shape signatures are located at a cutoff

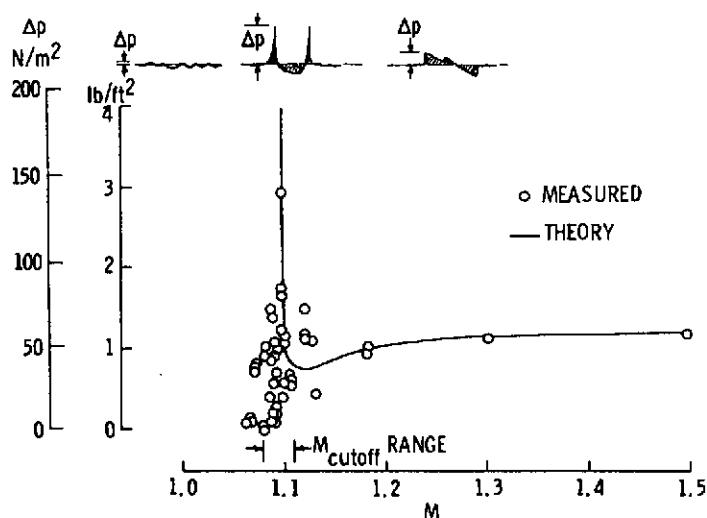


Figure II-73.- Variation of sonic-boom overpressure with airplane Mach number for an F-104 in steady level flight at 10.26 km (33 700 ft).

Mach number of  $M = 1.1$ .

At Mach numbers below  $M = 1.1$  very low overpressure levels were measured, and these were associated with the acoustic type of signature shown at the top left of figure II-73. At Mach numbers greater than  $M = 1.1$ , normal N-wave types of signatures were observed from which the pressure increased gradually with increasing Mach number as predicted by theory. Near  $M = 1.1$ , U-shape waveforms were generally observed. The predicted overpressure values would approach infinity because of the presence of the caustic line. The measured caustic signatures generally indicate overpressure enhancement compared with those associated with the higher Mach numbers. The highest enhancement factor suggested by the data of figure II-73 is 3. The experiments also suggested that very stable conditions of the atmosphere, especially the lower layers, are required to produce the U-shaped signatures of high overpressures.

### Summary of Results

The information derived from a number of recent flight and wind tunnel studies is summarized in figure II-74, in which are shown the variations with Mach number of the nominal overpressures for cruising flight in the low supersonic, supersonic, and hypersonic operating regimes. The hatched area represents the amount of boom minimization that may be attainable through airplane design.

Above a Mach number of about 2, increasing Mach number results in decreasing

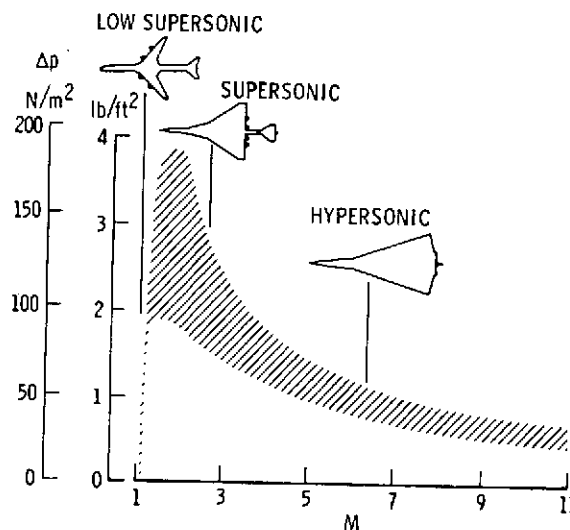


Figure II-74.- Variation of sonic-boom overpressure along ground track with airplane cruise flight speed.

overpressure. The decrease in overpressure results primarily from the increased altitudes required for flight efficiency and range as the speed increases. In attaining cruising Mach numbers, however, both the supersonic and hypersonic vehicles would pass through the low altitude Mach number region, where higher overpressures would be experienced. As the cruise Mach number is increased, sonic-boom minimization through airplane design is shown to be less effective.

Perturbations on the nominal values can be expected as a result of routine operations in the atmosphere. In addition, pressure enhancement resulting from maneuvering flight would also increase the nominal overpressure values. Certain of the overpressure buildups resulting from maneuvering flight are unavoidable; however, others are avoidable or can be minimal. Studies, thus far, suggest that the atmospheric and maneuver pressure enhancements are not additive. In conducting low supersonic operations intended to prevent shock waves from extending to the ground, great care must be exercised to match airplane operations to local weather conditions to avoid the sudden onset of large amplitude transonic booms.

#### Planned Research

Planned research relates directly to developing improved understanding of the minimization of nominal boom intensity and the prediction of occasional pressure enhancements or focusing due to accelerated flight and to atmospheric inhomogeneities. The reduction of the nominal sonic boom intensity by configuration shaping is under continuing study and involves the use of analytical computer studies and complementary wind tunnel tests. The development of improved prediction methods for focused booms involves analytical studies and related precision measurements in focus regions by means of controlled acceleration rocket sled tests.

#### POWERED LIFT AIRCRAFT

Commercial powered lift aircraft will be needed to reduce congestion around our major cities. They will probably be operated from existing and/or new airports, with short runways, in or very close to cities. The cost and complexities of the lift and propulsion systems will probably limit their use to short-haul applications.

The powered lift effort presently is being concentrated on three principal aircraft types:

- (1) The augmentor wing (AW)
- (2) The externally blown flap (EBF) with engines located under the wing (UTW)
- (3) The EBF with engines located over the wing (OTW)

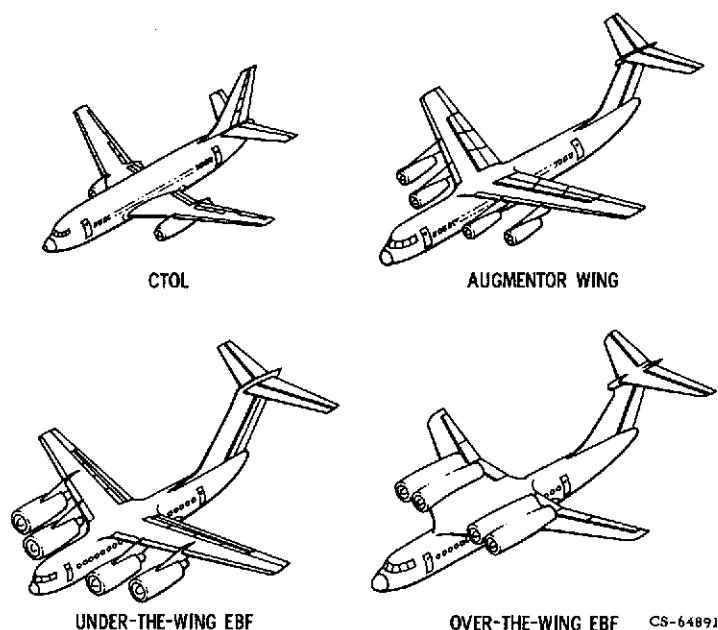


Figure II-75. - Short-haul and CTOL aircraft.

These aircraft concepts are shown in figure II-75 compared to a conventional CTOL aircraft. The EBF powered lift and propulsion systems are shown in figure II-76 and the AW system in figure II-77, together with the significant noise sources.

In all three concepts the exhaust from the propulsion system is directed onto or through the wing airfoil. Increased lift is thus obtained by the downward turning of the exhaust jet and by the increased flow induced around the wing by the jet.

Because powered lift aircraft will provide service out of heavily congested areas, the environmental specifications that will be imposed on them will be very severe. Extremely quiet and pollution-free operation will be demanded. Noise specifications for these systems have not been established; however, NASA has selected 95 EPNdB on a 500-foot sideline as a preliminary goal toward which to direct their research efforts (refs. 46 and 47).

Figure II-78 illustrates a 100 PNdB noise footprint for the DC-10-10 wide body jet compared with the footprint for a 95 EPNdB powered lift aircraft. Dramatic reductions in area are achieved by the 95 EPNdB aircraft. The severity of the noise goal can readily be appreciated by referring to figure II-79. This figure compares the present FAA FAR-36 noise requirement for conventional takeoff and landing (CTOL) aircraft, extrapolated to a 500-ft sideline measuring point, with the powered lift goal and the NASA quiet engine A. Note that the goal is approximately 30 PNdB lower than existing

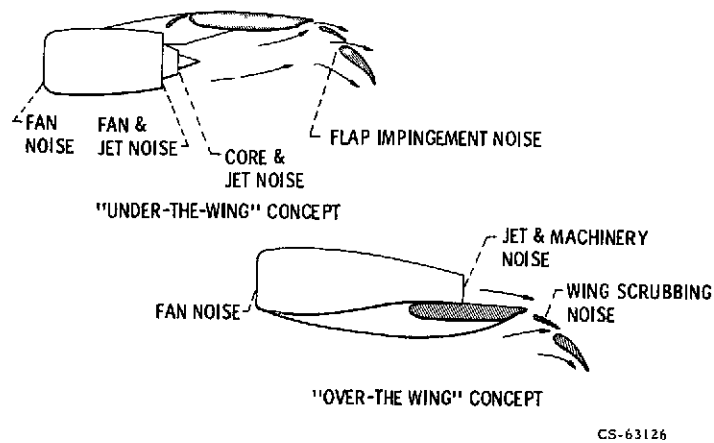


Figure II-76. - Blown flap powered STOL system.

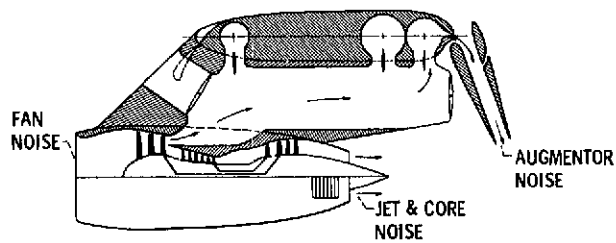


Figure II-77. - Augmentor wing propulsion system.

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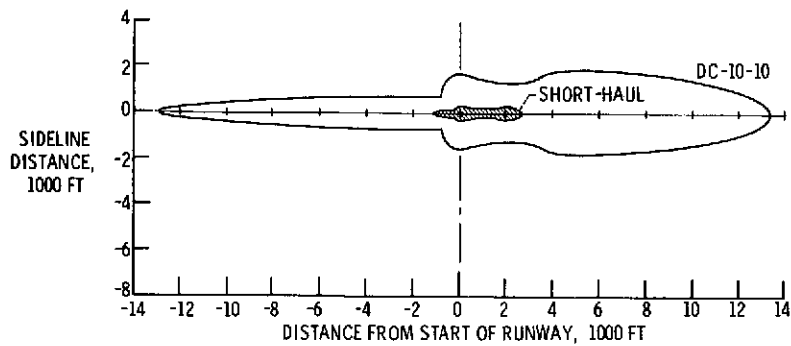


Figure II-78. - Estimated 100 PNdB noise footprints for a DC-10-10 and for short-haul airplane capable of 95 PNdB on 500 ft sideline. Mission 500 nautical miles.

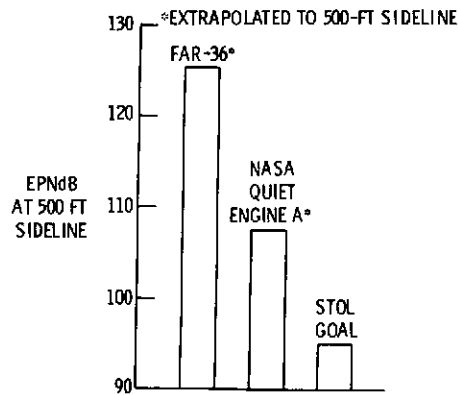


Figure II-79. - Sideline noise comparisons. Thrust, 90 000 lb.

regulations and 13 PNdB less than was achieved with quiet engine A. The effort required to achieve this goal is made more difficult because powered lift systems generate an additional noise source as compared to CTOL systems. The externally blown flap systems have flap impingement and scrubbing noise which results from the flow of engine airflow over and against wing and flap surfaces. The augmentor wing lift system has augmentor noise from the discharge of a high pressure jet into the flap system. Additionally, when comparing powered lift aircraft noise to CTOL noise, one finds that there is an approximate 3-dB penalty associated with powered lift systems due to the fact that their thrust-weight ratios are roughly twice those of CTOL systems.

This difficult noise goal now dominates the design of AW and EBF aircraft as is shown in the following sections.

## AUGMENTOR WING NOISE

The AW and its propulsion system together with the major noise sources were shown in figure II-77. The fan exhaust of the turbofan engine is ducted upwards through the pylon to the rear of the wing. At this point, the exhaust air is distributed span-wise and then discharged aft between two parallel flap segments. The flaps are set at different angles for takeoff and landing. In the cruise mode, the flaps retract and the fan air is ejected through a separate nozzle. Ejecting the wing air between the two flaps creates an ejector action which augments the lift but, more importantly, augments the forward thrust by an amount that more than makes up for any duct pressure losses. Current AW designs require fan pressure ratios of about three to meet wing volume requirements and noise restrictions (refs. 48 and 49).



Reduction of fan machinery, core, and core jet noise represent problems similar to those described under the SUBSONIC TRANSPORT AIRCRAFT section except that the more stringent powered lift aircraft noise goal further compounds the problem.

The AW fan is a multistage high pressure ratio fan and, as was shown earlier, is very noisy. The fan noise which radiates forward must be reduced about 30 dB to meet the goal. The sonic inlet previously described has the potential of providing this suppression. The fan noise radiated rearward is contained within the takeoff and distributor ducts to the wing and can be suppressed with acoustic wall treatment. The internal core noise originating from the turbine, combustor, etc., may be reduced using techniques described earlier except the lower levels desired makes the problem even more difficult. Core jet noise may be reduced to the required level by extracting more energy from the core flow to reduce its velocity to about 800 ft/sec. The resulting engine cycle will have a fan pressure ratio of about 3 and a bypass ratio about 2.5.

Without suppression and using a single rectangular slot as a wing exhaust, the high pressure fan exhaust flow discharges from the wing nozzle at 1200 to 1300 ft/sec and produces noise levels in excess of 115 PNdB at a 500-ft sideline if incorporated on a 100-passenger aircraft (refs. 50 to 53).

Since noise levels are unacceptable, NASA conducted a 2-year program with The Boeing Company to improve the augmentor wing performance to reduce and suppress the noise. The program included static thrust and noise tests of nozzles and nozzle-flap combinations, wind tunnel tests, and design integration studies.

Instead of the single rectangular slot nozzle employed in the early programs, Boeing studied the use of a wing nozzle design that had many small lobe nozzles. The use of multiple nozzles increased the ejector action of the flaps and hence the thrust augmentation of the system. More importantly, the several small, multiple nozzles raised the frequency of the jet noise which allow the practical use of acoustic treatment on the interior flap surfaces. (Acoustic treatment thickness is related to the noise wavelength.) The improved ejector action entrained more ambient air which mixed with and reduced the jet velocity exiting from the flap system to below 500 ft/sec. Thus, the wing nozzle-jet noise is effectively contained and suppressed within the flap system. A sketch of a full augmentor installation is shown in figure II-80 including details of the ducting and the multiple lobe nozzles (ref. 52).

The noise reductions obtained by the various steps taken in this development are shown in figure II-81 in terms of the 500-ft sideline noise level as a function of the nozzle pressure ratio. The term "soft flap" refers to the use of acoustic treatment. The noise level of the final optimized system is seen to be below the 95 PNdB goal for all pressure ratios of interest. Finally, the unsuppressed and suppressed noise levels of all the component noise sources are shown in figure II-82 for a typical short-haul transport. All sources have been suppressed sufficiently to attain the 95 PNdB sideline goal for the total aircraft (ref. 53).

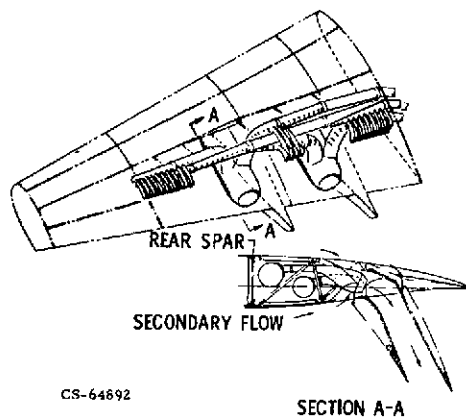


Figure II-80. - Augmentor duct and nozzle details.

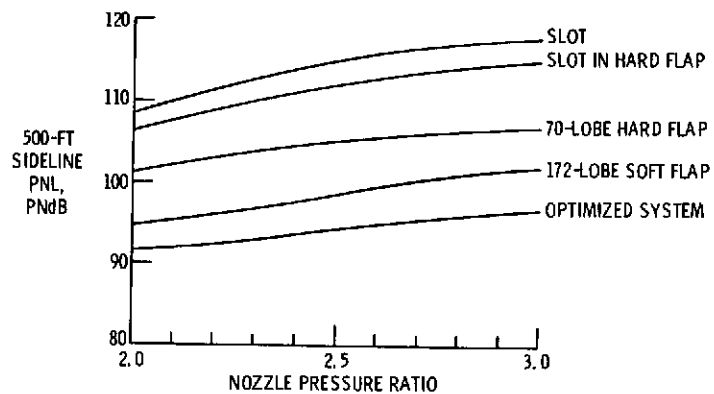


Figure II-81. - Augmentor jet-flap noise reduction. Four 20 000-lb SLS thrust engines; takeoff, 100 KTS.

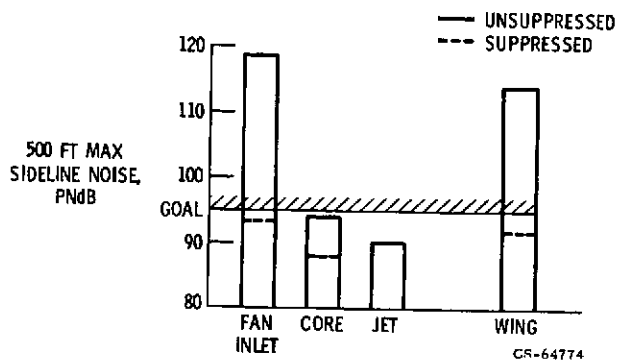


Figure II-82. - Augmentor wing component noise sources. 4 Engines, 80 knots; 60 000-lb thrust; 3.0 fan pressure ratio.

All the testing under the Boeing contract was at small scale (approximately 1/6). Current plans for future research on the AW systems include the procurement for acoustic testing at the Lewis Research Center of a full scale, partial spanwise section of a wing. This test configuration will have the latest and most advanced nozzle, flap, and acoustic treatment designs. Preliminary planning is currently underway with respect to testing a semispan augmentor system in a large wind tunnel. This system would use real engines and have realistic ducting and valving.

Research to date has indicated that an AW short-haul aircraft can be designed to meet the stringent noise goals.

## EXTERNALLY BLOWN FLAP NOISE

In the EBF systems, lift augmentation is achieved by locating the propulsion systems so that the exhaust gasses impinge on (or are directed over) the wing-flap system and then deflected downward. Lift augmentation comes about by the reaction to the downward jet deflection and also by inducing a favorable pressure distribution on the wing-flap system.

The noise generated by both the UTW and OTW blowing systems consists of the noise of engine itself, fan machinery, core and jet noise, plus wing scrubbing noise, and flap leading and trailing edge noise (see fig. II-76). The OTW installation has an additional noise source if a deflector is used to position the jet so that it attaches to the wing surface. However, the OTW installation provides a major acoustic benefit in that the wing-flap system shields a substantial amount of the noise in flight.

Reduction of the noise generated by the jet-wing interactions dominates the design of the EBF aircraft and engine acoustic design as will be shown.

The data in the subsonic aircraft jet noise section showed that, if a noise level of 95 PNdB is to be achieved, a jet velocity less than 850 ft/sec is required for both the fan flow and core flow. For the EBF powered lift systems, it has been found that still further reductions of exhaust velocities are required to reduce the powered lift source noise (e. g., flap impingement and wing scrubbing) to the desired level. Studies have indicated that the most economical means of achieving these low velocities is with high bypass ratio engines to achieve low core velocities and low fan pressure ratios (FPR) to achieve low fan exhaust velocities. Engines with FPR of 1.25 to 1.30 and bypass ratios of 12 to 20 appear optimum for EBF UTW. Because of the wing shielding effects slightly higher FPR's of 1.30 to 1.35 and bypass ratios of 10 to 16 appear optimum for EBF OTW installations.

These low pressure ratio fans are quieter than CTOL fans but still require significant noise suppression to meet the noise goal. The use of conventional acoustic suppression in conjunction with the high velocity inlets, described earlier, should provide

this suppression.

Core noise suppression presents a similar, equally difficult, problem to that encountered with the AW.

The major new acoustic problem, jet-flap noise, is now discussed in detail.

Research and development activity in the UTW (refs. 55 to 57) and OTW area has consisted largely of small-scale cold gas tests of various exhaust nozzle and wing sections plus two full-scale engine test programs. The large-scale tests were conducted with a CF700 engine and F-111 wing and flap and with the highly suppressed TF-34 engine, discussed earlier, with a triple slotted EBF wing section.

Plotted in figure II-83 are the results from large-scale cold gas tests which compare the noise patterns for both the upper surface and lower surface blowing powered lift systems (refs. 58 to 61). The noise directionality and the shielding of the OTW installation are evident. Results of all testing to date show that flap noise can be controlled mainly by reducing the impingement velocity of the fan and core air stream. Results from cold gas model tests, shown in figure II-84, indicate that only relatively low exhaust velocities will provide a noise level acceptable for STOL systems (refs. 62 and 63). These low velocities are not typical of today's fan engines and can best be achieved with fan pressure ratios of about 1.25. Lower flap impingement velocities can also be obtained with special exhaust nozzles (mixer decayer) which break up the fan stream into smaller jets, thus producing more rapid mixing and large velocity decay over a shorter distance (refs. 64 and 65).

The TF-34 engine and acoustic nacelle were evaluated with various nozzle combinations and decayers (fig. II-85) with a wing section for both the UTW and OTW configurations. Results of this program are summarized in figures II-86 and II-87. Sche-

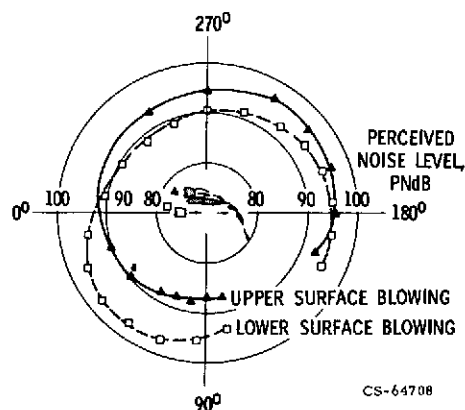


Figure II-83. - Comparison of EBF perceived noise level patterns at 500 ft. Nozzle diameter, 13 in.; wing chord length, 7 ft; flap position,  $30^\circ$  -  $60^\circ$ ; exhaust velocity, 680 ft/sec.

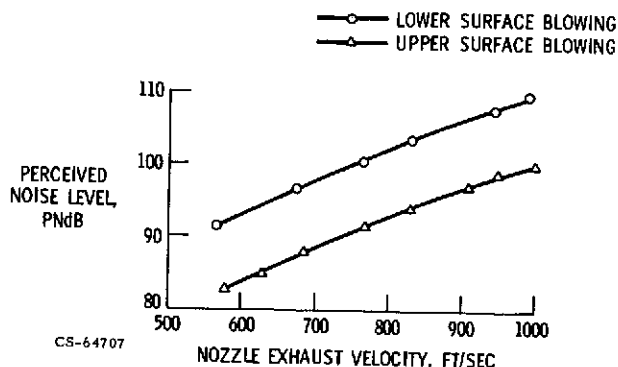


Figure II-84. - Effect of nozzle exhaust velocity on EBF perceived noise level at 500 ft. Nozzle diameter, 13 in.; wing chord length, 7 ft; flap position,  $30^\circ$  -  $60^\circ$ .

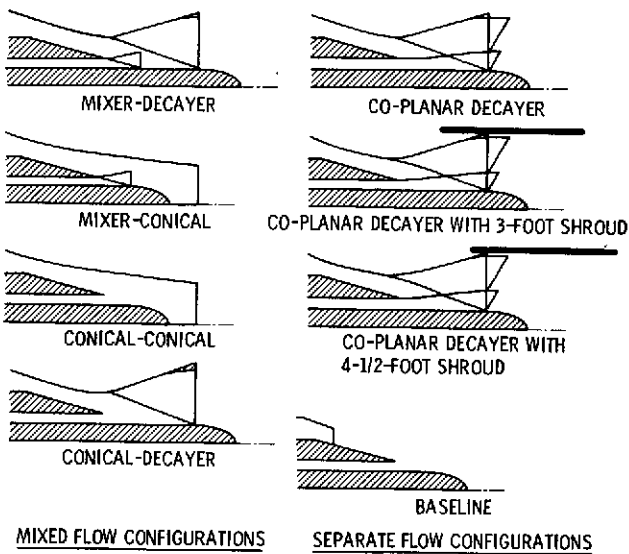


Figure II-85. - TF-34 exhaust nozzle configurations.

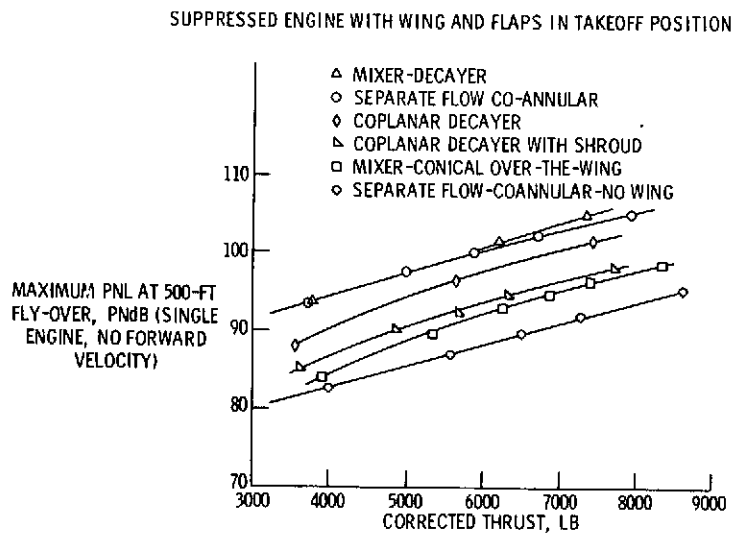


Figure II-86. - TF-34 noise comparison for various exhaust nozzle configurations.

matics of the nozzle configuration tested are shown in figure II-85. For the takeoff flap configuration, it is seen (fig. II-86) that the flyover suppressed engine noise, with no wing, increased approximately 12 PNdB when the fan and core flow from a separate flow coannular nozzle impinged on the flaps. A 12-lobe internal and external mixer-decayer was installed to reduce the impingement velocity. It was found, however, that although the velocity decay achieved was more than required, 8 PNdB of noise were generated by the mixer-decayer (fig. II-87). Tests of the mixer-decayer with the wing and flap system produced a noise level increase of 13 PNdB over that from the suppressed engine without wing. A redesign of the decayer proved effective in reducing mixing noise. To reduce the mixing noise still further, an acoustic shroud was placed over the decayer. With this final configuration, it was found possible to limit the UTW noise to an increase of 5 PNdB over that of the suppressed engine without a wing. All the previous results are shown plotted (fig. II-86) for a flyover noise condition. Measurements were also made to establish the sideline noise with the various test configurations. These data (fig. II-87) resulted in an average sideline noise reduction of 5 PNdB from that of the flyover noise. This reduction was due to directionality differences in the noise patterns from the flyover to the sideline measuring points. The sideline noise for the best UTW exhaust configuration was equal to that of the suppressed engine without a wing.

One test was conducted to establish a data point for the noise of an OTW lift system using a TF-34 engine. The quietest suppressed engine exhaust configuration was used,

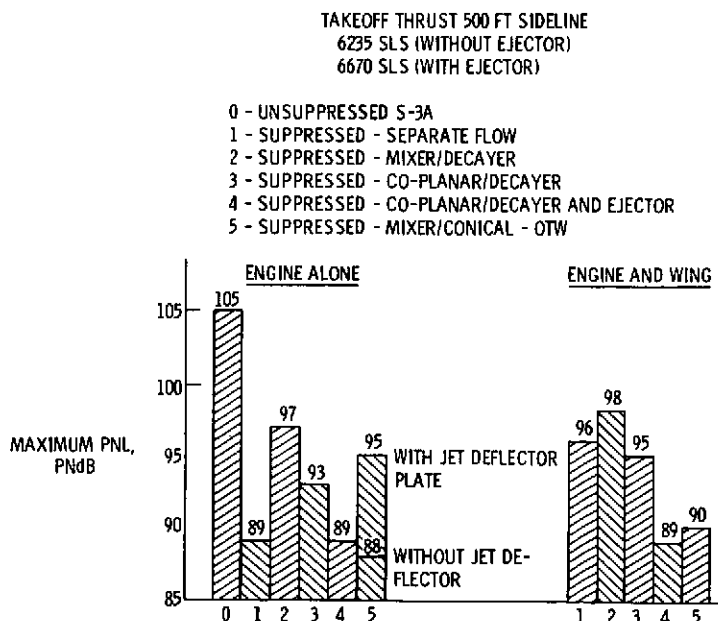


Figure II-87. - TF-34 noise summary.

which was an internal core mixer discharging into a conical fan exhaust duct. A deflector plate was added to the exhaust exit to attach the flow to the wing. A penalty of 7 PNdB resulted from the use of the deflector plate (fig. II-87).

Figure II-86 shows that the OTW flyover noise is quieter than that obtained with the best UTW exhaust system. The sideline noise was found to be only 1 PNdB higher than that of the suppressed engine by itself.

## QCSEE PROGRAM

The Quiet, Clean Short-Haul Experimental Engine (QCSEE) Program is a major element in NASA's quiet powered-lift propulsive technology program. It is being undertaken to establish the technology base for very quiet propulsion systems, designed for installation in powered-lift aircraft.

The major objective of the QCSEE Program is to develop and demonstrate the technology required for propulsion systems for quiet, clean, and economically viable commercial EBF powered lift short-haul aircraft. As was shown, quieting the aircraft is the most challenging problem.

The QCSEE Program consists of a definition phase already completed which has defined the engine for the short-haul powered-lift aircraft, and a hardware fabrication and testing phase to provide a demonstration of a quiet, economically feasible experimental EBF propulsion system.

The definition phase was initiated with in-house studies in May 1971. Two QCSEE propulsion system study contracts with Allison and General Electric were completed in January 1973 (refs. 66 to 69). In order to strengthen the engine definition phase, the two parallel aircraft system study contracts described in the next section were also conducted. The engine contractors, aircraft contractors, and NASA worked closely together to define optimized economically viable quiet propulsion systems for the UTW, OTW, and augmentor wing powered-lift concepts. Results from these major study efforts and the component technology programs were used to define the optimum propulsion systems for short-haul aircraft.

The component program was conducted in-house and under contract. It is providing a sound technical background for the engine studies and will be used in the future QCSEE design efforts. The programs include

- (1) EBF Fan Aero Development
- (2) EBF Fan Acoustics
- (3) High Mach Number Inlet Development
- (4) Acoustic Suppression Development
- (5) EBF Flap Noise Reduction

These programs were summarized earlier. Details are, or will be, available in forthcoming NASA reports.

The completed program effort has indicated that the noise goal can be met by unique design approaches, but more extensive testing of large-scale propulsion and powered lift systems are essential before the full extent of the cost is determined.

The effort has shown the following:

(1) A variable pitch fan (1.25 to 1.30 pressure ratio) propulsion system on an EBF-UTW aircraft might meet the noise goal without excessive cost penalties. Figure II-88 is a sketch of this engine.

(2) The AW and EBF-OTW systems also have a good potential for meeting the noise goal with more conventional propulsion systems. The installation of these propulsion systems in the aircraft, however, presents many unique problems.

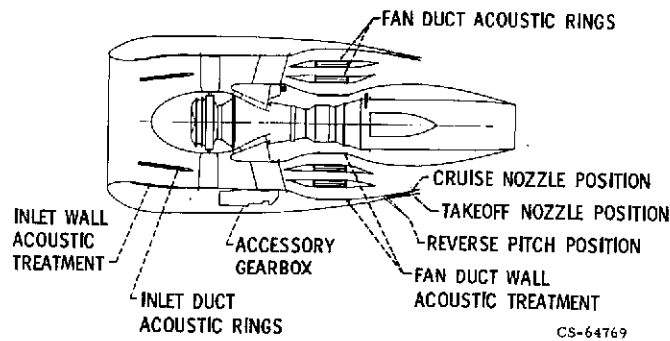


Figure II-88. - Variable pitch fan engine, EBF aircraft (UTW).

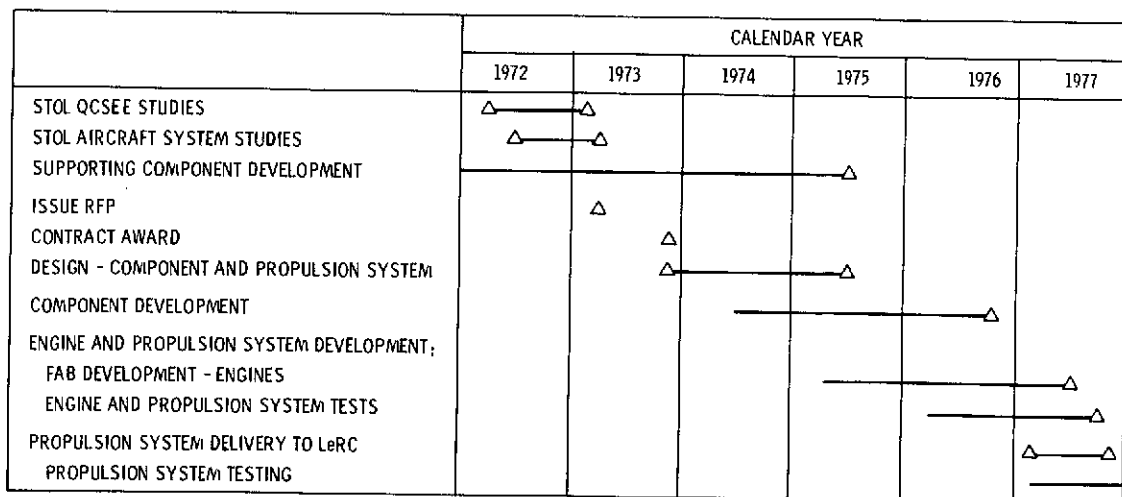


Figure II-89. - QCSEE program plan.



The second phase of the QCSEE Program will concentrate on the development of the variable pitch fan engine and the "quiet" nacelles for EBF OTW and UTW installations.

Figure II-89 depicts the plan for the QCSEE Program using current fiscal guideline restraints.

## NASA SHORT-HAUL AIRCRAFT SYSTEM STUDIES

In parallel with the QCSEE studies, contracts were let to the Douglas Aircraft Company and the Lockheed Aircraft Company to perform a "Study of Quiet Turbofan STOL Aircraft for Short-Haul Transportation." These contracts were managed by the Advanced Concepts and Mission Analysis Division at Ames. Both contractors use inter- and intra-state airline companies as subcontractors. The contractors conducted an in-depth parametric aircraft (refs. 48, 49, and 70) design analysis of a large number of candidate aircraft concepts, sizes, and levels of performance; screened the large matrix of designs against a parametric transportation system representative of the national short-haul market; and designed six STOL aircraft. The aircraft companies also defined the optimum propulsion systems for these powered-lift aircraft. Both the engine manufacturers and the aircraft manufacturers maintained close liaison during the studies. The studies served to guide and to provide a sound basis for further R&D on viable quiet short-haul air transport systems.

Several powered-lift aircraft systems were analyzed. These included augmentor wing, externally (EBF) and internally blown flap with engines mounted both OTW and UTW. In addition, mechanical flap aircraft were analyzed for comparison to powered-lift systems for convention field lengths. A substantial part of the early study effort was devoted to evaluation of various engine candidates submitted by the QCSEE engine study contractors as part of the related contract.

From the studies, it was concluded that:

(1) A low fan pressure ratio (1.25), variable pitch fan was optimum for meeting the 95 EPNdB noise goal for EBF UTW aircraft with a 2000-ft takeoff field length.

(2) A higher fan pressure ratio propulsion system could reduce cost if the noise goal is relaxed 3 to 5 dB. The effect of this relaxation on the footprint area is shown in figure II-90.

The aircraft economic systems analysis showed that for field lengths below 3000 ft, all powered lift concepts are competitive costwise although there are differences in noise footprints as shown in figure II-91. For field lengths greater than 3000 ft, the conventional mechanical flap (MF) systems start showing economic benefits. However, fan pressure ratios are limited to less than 1.35 if a 95 EPNdB noise goal is to be met.

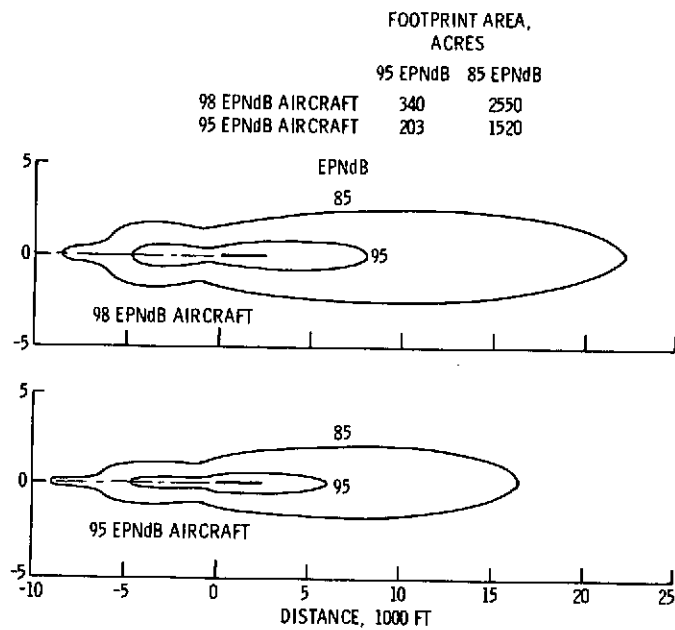


Figure II-90. - Footprint comparison of 98 and 95 EPNdB aircraft EBF-UTW 2000 ft field length, 125 Passenger aircraft.

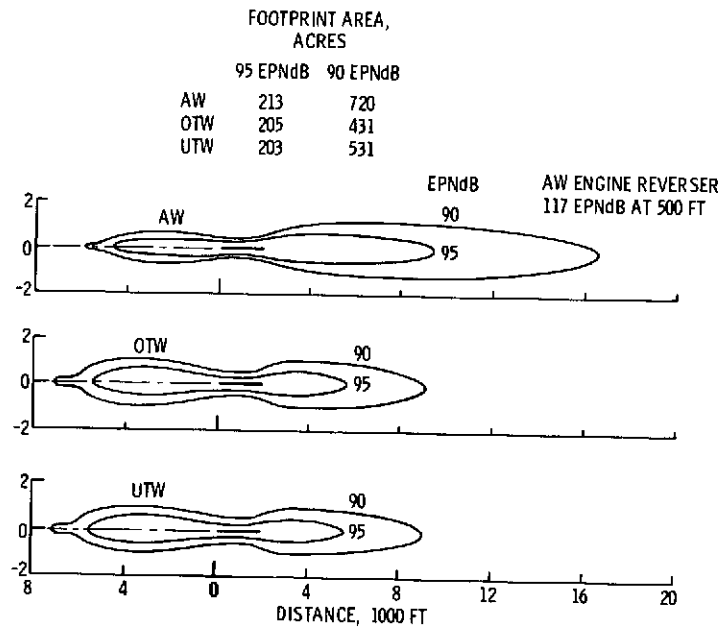


Figure II-91. - Footprint comparison of AW, OTW, and UTW aircraft, 95 EPNdB aircraft, 2000 ft field length, and 125 passenger aircraft.

## ROTORCRAFT

The two main sources of noise from the rotorcraft are the engines and rotors. The engines may be of the reciprocating, rotary, or turbine types, and their noise characteristics can thus vary widely. The noise source characteristics and the noise control technology approaches for gas turbine engines for rotorcraft are similar to those previously discussed for other types of flight vehicles and are thus not included herein. This section includes discussions of reciprocating and rotary engine noise sources and rotor noise sources.

### ENGINE NOISE

The dominant noise source for reciprocating and rotary engine powered helicopters is usually the engine exhaust if no muffler system is installed.

Muffler design methods that rely greatly on empiricism are available for providing significant exhaust noise reduction. Types of reactive devices that will accomplish this task are shown schematically in figure II-92 together with their transmission loss characteristics. Practical muffler systems consist of combinations of such devices. Although simple theory provides a guide for experimentally combining these devices into a workable muffler system, it has not provided realistic quantitative predictions of com-

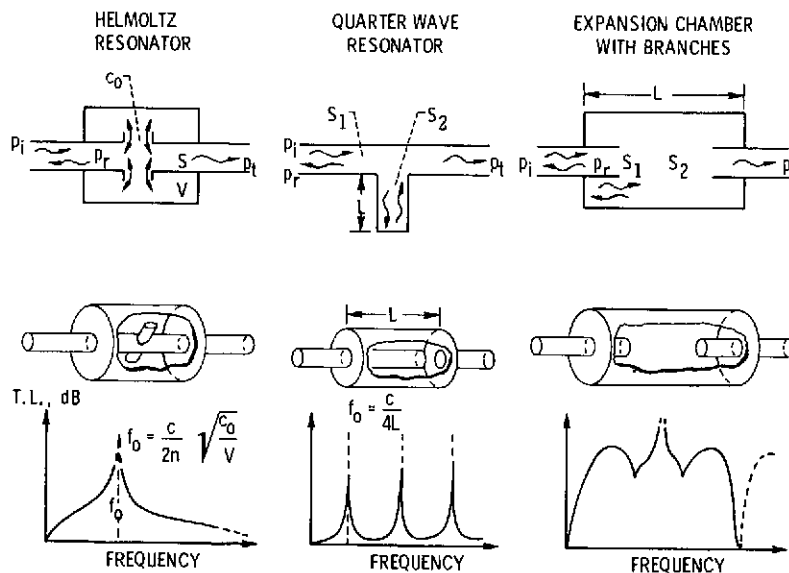


Figure II-92. - Schematic diagrams of the various types of reactive mufflers and their transmission loss characteristics. (From ref. 71.)

plex muffler system performance. At Langley, considerable effort has been devoted to developing a computer program that makes use of an improved theory for predicting the performance of combinations of expansion chamber type mufflers as shown in the sketch of the figure. In addition this computer program incorporates an optimization procedure that allows for some variation of muffler configuration to meet a specified minimum transmission loss characteristic.

The performance of a three-stage expansion chamber muffler for a helicopter engine is shown in figure II-93. In this figure the unmuffled helicopter noise spectrum is compared with the spectrum obtained with the muffler system installed. Clearly the spectrum for the modified aircraft is now dominated by rotor noise.

It is anticipated that the incorporation of the capability of handling other reactive devices as well as absorptive elements into a computer program will significantly enhance the practical usefulness of this analytical approach to muffler design. This possibility would require further basic research effort to determine the effect of operating parameters such as flow and temperature gradients on resonator performance. Also, further data would be needed on source impedance effects to predict total exhaust noise reduction.

To date, only a limited amount of experience is available regarding applications of exhaust mufflers to helicopters. It can be anticipated, however, that the normal payload will be reduced somewhat because of the additional weight of muffler, manifolding, etc., and there may be some relatively small power loss due to increased backpressure on the engine.

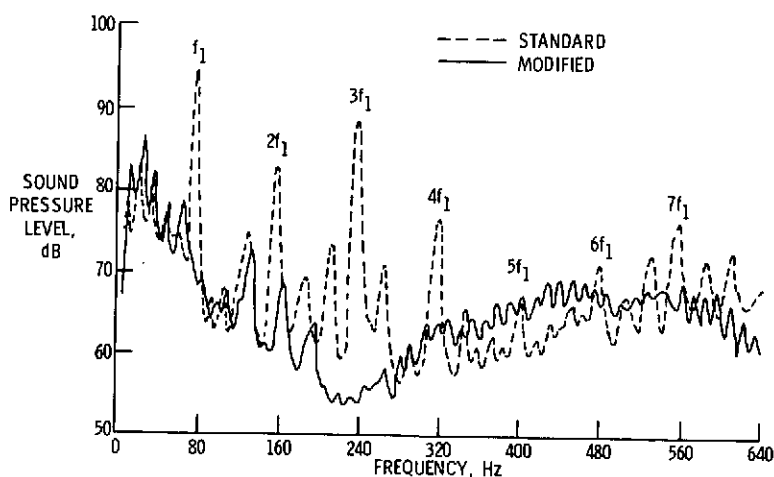


Figure II-93. - Comparison of noise radiation from helicopter in standard configuration and with modification to include exhaust muffler. (From ref. 72.)

## ROTOR NOISE

In the cases where either turbine engines or reciprocating engines with exhaust mufflers are used, the rotor noise may be the dominant noise component for helicopters. The major problems associated with helicopter blade noise reduction are (1) validation and expansion of existing prediction theories, (2) more exact understanding of the generation mechanisms of each noise category, and (3) reduction of the acoustic effect of the airflow mechanisms with as little performance penalty as possible.

Figure II-94 presents estimated relative perceived noise levels associated with helicopter rotor operation at various tip speeds and for a given thrust, along with indications of the significant sources of noise in the various operating regimes. With regard to steady loads, theories are available and have been validated for predicting the lower order harmonics. These predictions are appropriate for long-range detection and fuselage and wing structural response problems. They give results of acceptable engineering accuracy. With regard to the unsteady (periodic and nonperiodic) aerodynamic load sources, however, the available prediction theories have essentially not been validated. Figure II-95 illustrates the importance of the unsteady periodic aerodynamic loads in predicting periodic rotor noise.

High priority research items are the validation of the theoretical concept of fluctuating loads and the definition of operating conditions over which it is useful, and the identification of practical means of minimizing rotor noise for particular applications.

High-frequency blade surface pressure data are required before any significant progress can be made toward understanding aerodynamically generated sound. The occurrence of stall, the degree of compressibility, and the severity of blade-wake in-

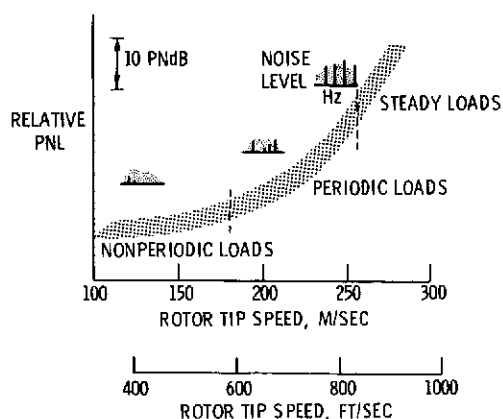


Figure II-94. - Schematic diagram relating perceived noise levels of unducted rotors as a function of tip speed for a constant rotor thrust. (See ref. 73.)

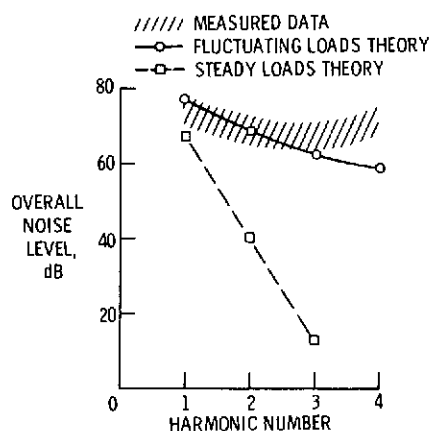


Figure II-95. - Comparison of measured and calculated helicopter rotor rotational noise for several harmonic numbers. (See ref. 74.)

teractions must be known in connection with three-dimensional transonic and supersonic dynamic airfoil characteristics. The azimuth position at which a rotor blade generates maximum sound must be specified accurately, a requirement which imposes much complexity both in analytical treatments and experimental flight-test data and analyses. Therefore, controlled whirl tower and quiet wind-tunnel testing of rotors with advanced blade aerodynamic and acoustic instrumentation holds the greatest promise of isolating and treating individual aerodynamic sound sources.

Figure II-96 indicates some of the methods being used to measure the aerodynamic inputs for the noise prediction theories. Emphasis in these programs is on the identification of trends in dynamic loading which can be related to standard lift and drag parameters.

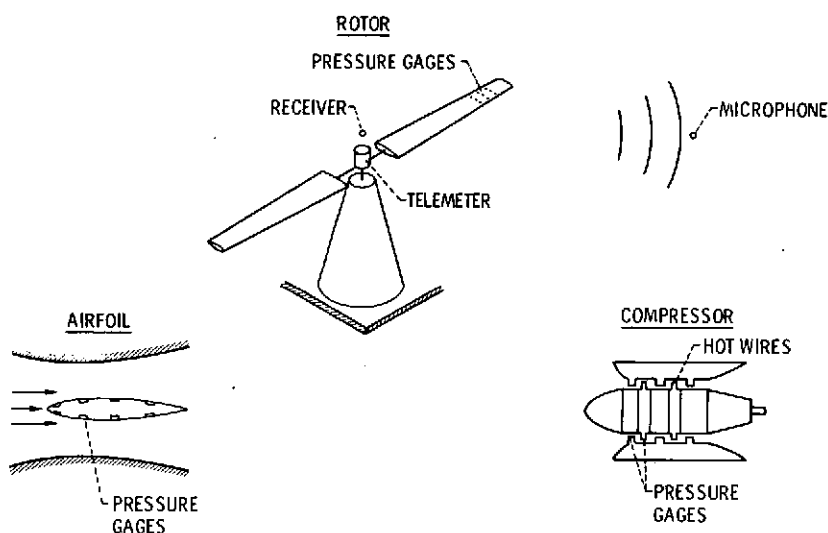


Figure II-96. - Three example measurement situations for obtaining fluctuating blade loads information.

A recent collaborative effort by the DOD and NASA to use existing technology to reduce helicopter external noise resulted in the Quiet Helicopter Program. Three different types of helicopters were modified in this program and were evaluated from an acoustic and performance standpoint. Modifications to the helicopters included the addition of blades to both the main and tail rotors, reduction of main and tail rotor rotational speeds, different rotor blade tip shapes, engine inlet and exhaust noise suppression, and miscellaneous noise control work directed at the power train. Differing amounts of noise reduction were obtained with the various helicopters. Figure II-97 shows the helicopter which demonstrated the largest overall ontrack noise reductions (approx. 14 dB) of the three tested (see ref. 75).

In certain helicopter flight conditions, the predominate noise source is rotor blade

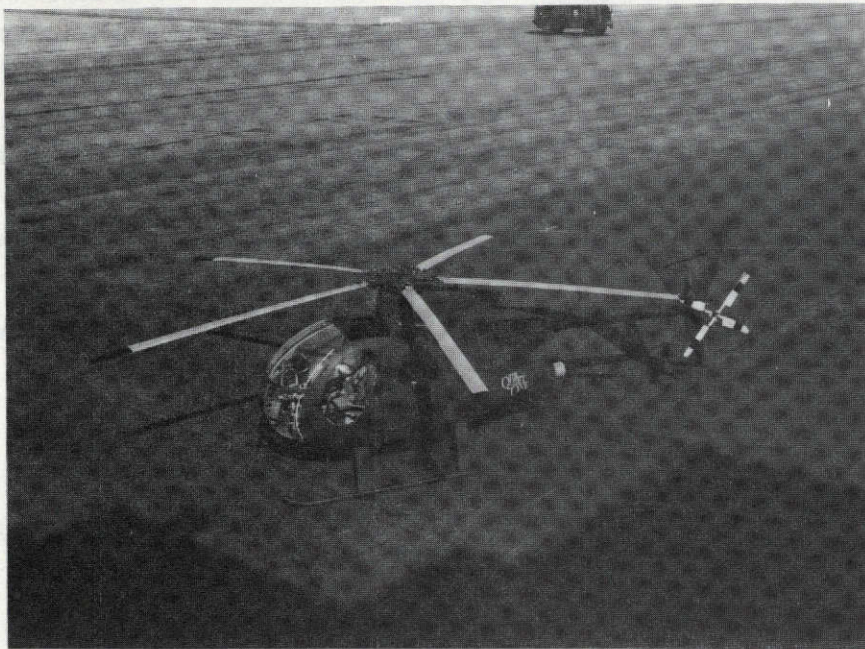


Figure II-97. - The Hughes OH-6A helicopter modifications to reduce external noise.

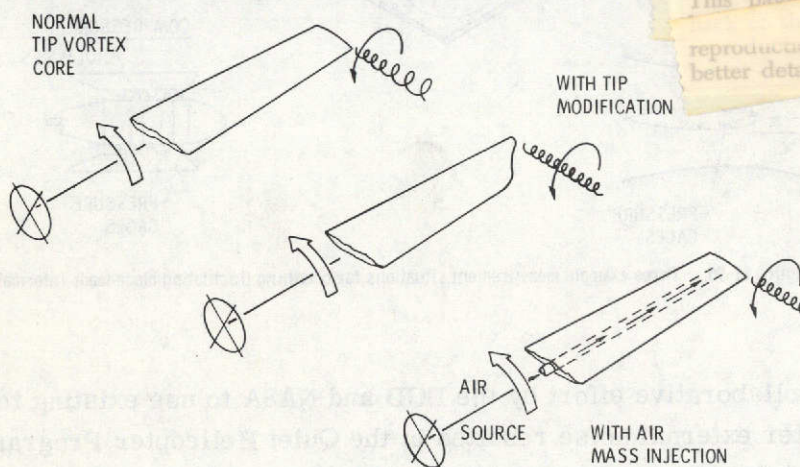


Figure II-98. - Schematic illustrations of two methods of blade tip vortex dissipation for noise reduction purposes.

"bang." This impulsive noise is caused by localized impulsive aerodynamic loading which occurs periodically. The low-speed periodic loading occurs when a blade passes close to a wake vortex filament and experiences a change in angle of attack. Several methods are proposed for reducing impulsive noise due to blade/vortex interactions; these are illustrated in figure II-98. The first method involves the passive diffusion of the tip vortex by an ogee tip, the second method is an active system which affects the vortex strength by air mass injection.

## PLANNED RESEARCH

Programs planned for future helicopter rotor research are (1) measurements of fluctuating pressure patterns on a static airfoil at various angles of attack for correlation with radiated noise, (2) studies of the effects of tip mass injection to alleviate noise associated with the tip vortex structure, and (3) studies of the effects on radiated noise of nonuniform inflow to the rotor disk. In all rotor noise tests the acoustic results will be correlated with performance data. The trend toward lower tip speed rotors for noise control will probably result in relatively heavier blades and hubs.

## GENERAL AVIATION AIRCRAFT

General aviation aircraft constitute the fastest growing segment of the aircraft industry. They are operated in both urban and rural areas and usually at relatively low altitudes. The main noise sources are the engines and the propellers. Internal combustion engines provide the power for the large majority of general aviation aircraft and, because of economic considerations, this situation will probably continue for a long time. Turboshift engines are preferable from a noise reduction standpoint but are markedly more costly. The procedures for internal combustion and gas turbine engine noise control have already been discussed in the previous sections and are thus not included herein. This section includes discussions of propeller noise and the general technology associated with quiet general aviation vehicle design.

## QUIET VEHICLES

The development and demonstration of relatively quiet single engine propeller driven aircraft has extended over approximately a 25-year period and several specific flight test projects have evolved (see refs. 76 to 80). The resulting quieted aircraft



have involved the use of engine exhaust mufflers, modified propellers and gear boxes for reduced noise, and in some cases provisions for intake and accessory noise control. These flight vehicle projects have demonstrated the basic technology required for development of quiet general aviation vehicles.

## QUIET PROPELLERS

Quiet propellers generally involve lower tip speed operation and multiblade designs. Theories are available for predicting the noise both near the propeller as it may affect the fuselage and its occupants and in the radiation field. Prediction of the noise due to steady loads on the blades has been well established and confirmed by experiments (see refs. 81 and 82). Methods of predicting noise due to the unsteady loads on the blades are still in the process of development. Theories are available, but complementary experimental information is lacking. Flow induced fluctuating pressures on the blades are believed to be important in the prediction of the higher frequency noise components significant in subjective reaction. These fluctuating pressures may be due to nonuniform in-flow to the propeller disk as a result of atmospheric turbulence, configuration asymmetries, and thrust axis inclination.

Some performance penalties may be expected due to the quieting of general aviation aircraft. These can take the form of reduced payload because of the additional weight of mufflers and multiblade propellers, reduced cruise speed, reduced range, and increased takeoff distance. In several situations, evaluations have been made of performance penalties associated with specified amounts of noise reduction (see refs. 76, 79, and 80).

One finding of recent studies is that the propellers currently used on general aviation aircraft are not necessarily well matched to the engine and airframe. Thus, an optimized propeller may be able to provide a substantial improvement in noise with a minimal effect on the performance of the aircraft.

Planned research will be oriented to developing and confirming methods for high-frequency propeller noise prediction. This will involve precision acoustic and aerodynamic measurements in quiet wind tunnel environments, such as the Aircraft Noise Reduction Laboratory, to provide empirical inputs to the theories and to provide overall validations. Some limited in-flight studies are also required for correlation.

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### III - OPERATING PROCEDURES FOR AIRCRAFT NOISE REDUCTION

Operational procedures can be used effectively for noise control in both landing-approach and the takeoff-climbout phases of the mission. The interrelated factors of aircraft altitude, engine throttle setting, flap angle setting, and aircraft speed are significant.

NASA, in cooperation with FAA and the airlines, has been involved in developing and evaluating operational procedures for noise reduction for a number of years, both for takeoff-climbout and landing-approach situations. The takeoff-climbout studies (refs. 1 to 4) have been helpful in evaluating the noise reduction potential for various flap angle and engine throttle schedules for a number of aircraft. These data have also been useful as a guide in defining the optimum procedures for particular operations.

A main finding of these takeoff-climbout studies is that the optimum conditions for noise alleviation depend on the configuration details (particularly, type of engine) and operating characteristics of the aircraft and thus will probably be different for each new aircraft. The landing-approach studies on the other hand have indicated potentially larger noise reductions, and they are not so configuration oriented. Three noise reduction techniques that have been proposed are the two-segment approach, the energy management or decelerating approach, and the curved ground track approach.

The two-segment approach concept is illustrated in figure III-1. The upper profile represents the two-segment approach, and the lower profile is a standard instrument landing approach. Using the two-segment approach, the aircraft approaches on a steeper

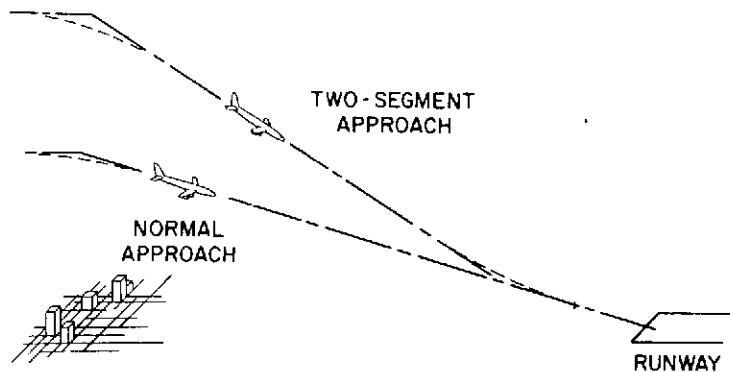


Figure III-1. - Two-segment approach concept.

than normal glide slope and then makes a transition to the standard approach path in time to stabilize before landing. By keeping the aircraft higher above the ground and reducing the engine power because of the steeper angle, the two-segment approach lessens the community noise near airports.

In the energy management or decelerating approach, the aircraft initiates the approach at a relatively high airspeed and then slowly decelerates to landing speed at greatly reduced power. Because of the reduced power, the noise under the approach path is reduced. The decelerating approach is attractive because it has the potential of providing some noise relief all the way to the threshold. This technique might be combined with the two-segment approach in order to use the best feature of each.

The third procedure is based on avoiding noise sensitive areas by approaches on a curved ground track. This technique is being used under visual conditions today. With the advent of area navigation and the microwave landing system, this technique can be extended to instrument flight conditions and combined with the two-segment approach.

Although these noise abatement flight procedures are well within the performance capability of current day jet transports, they impose new requirements on the pilot duties and workload, on the pilot displays, on the guidance and navigation system, on the aircraft control system, on Air Traffic Control (ATC) flow of aircraft to high density runways and on parallel runway operations, and possibly different wake turbulence effects. A substantial effort is therefore required to develop suitable avionics for noise abatement procedures and to obtain sufficient experience so that they are accepted for routine operations.

For the purpose of this report, the NASA program directed towards developing operational procedures for noise abatement is divided into two parts. The first part is aimed at developing operational avionics and flight procedures that will allow aircraft to make two-segment approaches under instrument flight conditions during routine scheduled operation. This part of the program is currently under way, and significant progress has been made. The second part is aimed at determining the feasibility of other techniques for noise abatement such as the decelerating approach or curved ground track approach. The second part of the program also addresses the problem of how to best utilize new navigational aids such as the microwave landing system. Work related to the second part of the program has not yet been initiated.

## PROGRAM HISTORY

The FAA and NASA have conducted several studies to obtain a preliminary determination of the feasibility of using modified operating procedures to reduce the noise perceived by the airport community. Both agencies have determined that significant

noise reduction can be achieved by using the two-segment approach. NASA has been primarily concerned with the evaluation of pilot displays that would be required to make noise abating two-segment approaches (refs. 5 to 8). The FAA has been primarily concerned with developing the necessary guidance systems (refs. 9 and 10). In these studies, experimental equipment was evaluated to assess concept feasibility.

NASA and American Airlines recently completed a program to incorporate the results of the previous studies into operational equipment. The goal of the program was to assess the operational feasibility of the two-segment approach as a method of reducing airport community noise (ref. 11). For these tests, an area navigation system was used to compute the upper segment, and the instrument landing system (ILS) glide slope was used for the lower segment. The localizer was used throughout the approach. A key feature of the program with American Airlines was the provision of a continuous vertical steering command on the flight director. This was required to insure that transitions from level flight to the upper segment could be made without overshoots and those from the upper to the lower segment could be made without going below the normal ILS. The additional power needed to correct for going below the ILS is particularly objectionable because it creates higher perceived noise on the ground in the region of the transition. This effect is illustrated in figure III-2.

The tests with American Airlines were conducted during a 30-day period in the summer of 1971 at the Stockton, California, Metropolitan Airport. Stockton Metropolitan Airport was selected for these tests because of the low traffic density and good visibility

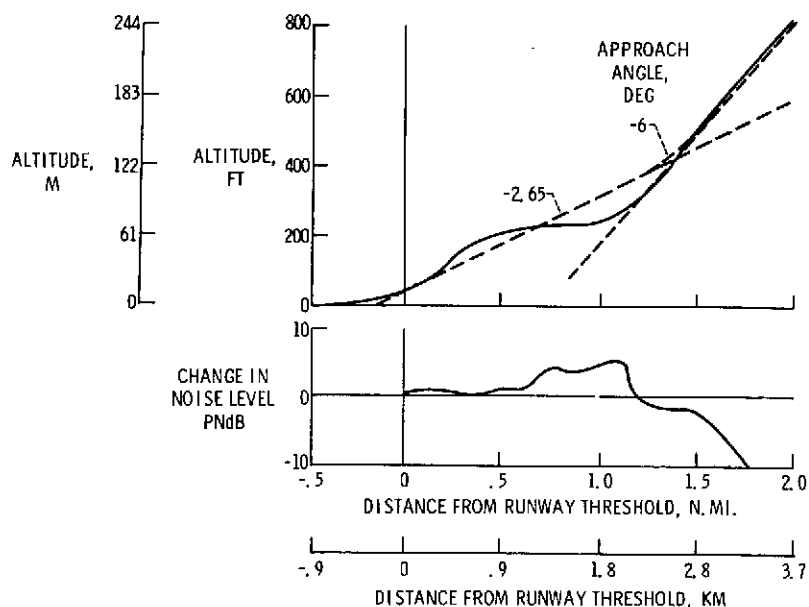


Figure III-2. - Effects of inadequate guidances.

prevalent during the test period. The program demonstrated that two-segment approaches might be operationally feasible and warranted a much more extensive and thorough evaluation under actual operational conditions.

The results of the program with American Airlines were presented to the NASA Research and Technology Advisory Committee on Aeronautical Operating Systems and to the Ad Hoc Panel on Noise Abatement by Operational Procedures. These advisory committees are composed of individuals representing the airlines, airframe manufacturers, avionics suppliers, the Air Transport Association (ATA), the Air Line Pilots Association (ALPA), FAA, and DOT. The committees agreed that the two-segment approach appeared operationally feasible and warranted additional evaluation. They recommended that further flight evaluations be conducted under representative operational conditions in two aircraft types: A Boeing 727 aircraft, because these aircraft account for the largest number of arrivals and departures and are owned by more air carriers than any other aircraft, and a long-range aircraft such as the DC-8 or Boeing 707 because these aircraft differ significantly from the Boeing 727 and have a larger noise footprint. The panel also recommended that the results of these two flight programs be extrapolated through analysis and simulation to determine the applicability of the two-segment approach to the other aircraft in today's fleet.

## TWO-SEGMENT APPROACH

The first part of this program consists of several steps. The first two steps are being conducted with United Air Lines and call for separate flight evaluations using a Boeing 727-200 and a McDonnell-Douglas DC-8-61, each equipped with different avionics for providing vertical guidance during the approach. The Boeing 727 will be equipped with a special purpose glide slope computer, and the DC-8 will be equipped with an area navigation system. Both systems will be designed and built by the Collins Radio Company under contract to NASA. The glide slope computer system is being evaluated as an inexpensive retrofit for aircraft not equipped with area navigation equipment. The area navigation system is being evaluated to determine the operational feasibility of modifying the existing airborne area navigation equipment to provide the two-segment capability. If the aircraft has an installed area navigation system, this concept appears to be the least expensive way to add the two-segment approach capability. Another step in this part of the program involves the extension of the flight results to the other aircraft in today's fleet.

## STEP A: DEVELOPMENT AND FLIGHT EVALUATION OF A SPECIAL PURPOSE GLIDE SLOPE COMPUTER IN A BOEING 727-200 AIRCRAFT

NASA Ames Research Center began work on this program with United Air Lines and the Collins Radio Company in July 1972. The program objectives are to develop an inexpensive avionics retrofit kit that will make an aircraft capable of a two-segment approach and to evaluate the two-segment approach in a Boeing 727-200 aircraft during regular scheduled service.

The program includes avionics design and fabrication; a simulation study aimed at developing a procedure and profile that is safe under adverse conditions; an engineering flight evaluation devoted to equipment checkout, certification, and verification of the approach profile established during the simulation study; a 1-month series of off-line flight evaluations; and a 6-month evaluation in revenue service.

The avionics design and fabrication, the simulation study, the engineering flight evaluation, and the off-line pilot evaluation have been completed. The results of these phases have not been completely reviewed and analyzed, but preliminary indications are that the avionics and two-segment approach are operationally feasible in the Boeing 727 and acceptable to the airline community.

In the simulation study the task was to make the concept into a practical, operational reality since the basic concept of the two-segment approach had been established by previous studies and research projects. In the design of the two-segment procedures, the basic profile was divided into eight parts as illustrated in figure III-3. The effect of

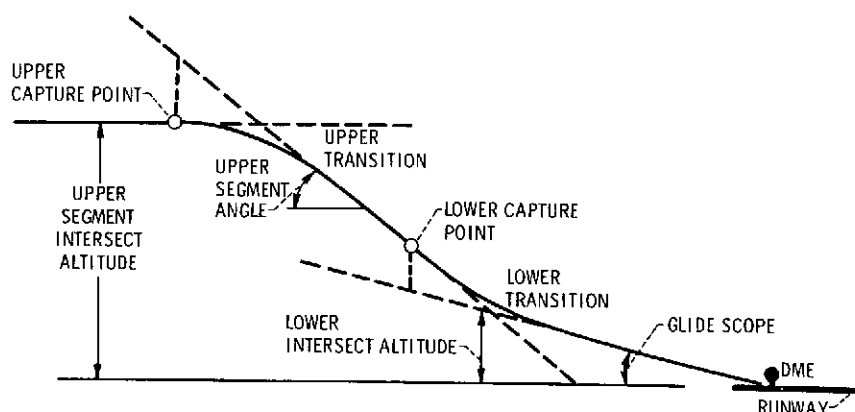


Figure III-3. - Noise abatement approach profile simulation variables.

each part on the approach was examined. Comments regarding these eight parts are contained below:

(1) Upper segment intercept altitude - The system must function such that this part can vary to 6000 feet (ft) altitude flight level (AFL) (and even higher is desirable). Also, it must not be fixed but either climbing or descending.

(2) Lower intersect altitude - This part was made to vary from 1500 ft AFL down to runway threshold height. A practical operational range would be smaller, but it was felt that its influence on the approach should be tried over this range.

(3) Upper segment angle - This part was made to vary from  $4^{\circ}$  to  $7^{\circ}$ , although  $8^{\circ}$  and  $10^{\circ}$  were added to check the validity of previous information about these descent angles.

(4) Glide slope - This part was expanded from the nominal glide slope range of  $2.5^{\circ}$  to  $3.0^{\circ}$  to  $3.5^{\circ}$ . The system was designed so as to provide a bias allowing the pilot to have guidance to hold the additional angle increment over the standard ILS glide slope.

(5) Upper capture point - This part was considered very important to the pilots acceptance and passenger comfort. It was so designed to compensate for varying closure rates to the upper segment angle.

(6) Lower capture point - This part was also considered important to safety, pilots acceptance, and passenger comfort. It was designed to compensate for varying closure rates to the glide slope.

(7) Upper transition - This part, important to passenger comfort, was designed to allow wide variations that enable the pilot to get to the upper segment without additional constraints or disturbances to the passengers.

(8) Lower transition - This part was considered the key to pilot acceptance and was designed so that the pilot could make this transition using a normal instrument close check and normal flight technique, and not feel that he was performing an unusual maneuver that would require him to restabilize the aircraft at its completion.

The effects of some of the external variables that the pilots might encounter were examined in the simulation. A summary of some of these are listed here:

(1) Turbulence - The two-segment approach during simulation was not adversely affected by turbulence. Any turbulence level flyable on the standard ILS was flyable on the two-segment approach. In the airplane the two-segment approach required less effort than the standard ILS when there was significant turbulence.

(2) Icing - With engine and wing anti-icing on and temperatures  $-7^{\circ}$  C or above, the low pressure turbine rpm is about the minimum of 55 percent. In these conditions a tail wind of about 15 knots can be offset by using  $40^{\circ}$  flaps. But if the icing is such that 70 percent  $N_1$  is required for anti-icing, or the tail winds are in excess of 15 knots, then the approach, as constituted, could not be flown. These conditions exist less than 1 percent of the time.

(3) Winds - Tail winds in excess of 30 knots present a problem of airspeed stabilization and throttle position. Less than 30 knots are maneuverable. Cross wind effect is the same as the standard ILS. Wind shear effect is very similar also, except that the upper segment can be followed easier than the glide slope when troublesome wind shear is present.

(4) Visibility - No noticeable difference between the two-segment approach and the standard ILS was detected.

(5) Lighting - The two-segment approach profile permits a better view of the terminal area under all lighting conditions than does the standard ILS, yet the descent angle is not so steep as to give the pilot the impression of his descending into a hole at night.

(6) Airports - The relationship of the two-segment approach and the standard ILS is very similar at Los Angeles, San Francisco, and Stockton.

(7) Navaid failures - No difference, except that the colocated distance measuring equipment (DME) adds in one more system that must be in operation for the two-segment computer to function.

The two-segment approach that resulted from the simulation evaluation was used in the engineering flight evaluation. The upper intersect altitude was designed to go as high as 6000 ft AFL. The altitude was tested and found successful up to 14 000 ft (mean sea level). The upper and lower capture points occurred as designed and were very satisfactory. The upper segment angle was selected to be  $5.2^{\circ}$  to  $7.0^{\circ}$ . The lower value was found to have good noise improvement when associated with low-lower intersect altitudes. It also allowed the Boeing 727 to use full anti-ice capability when  $40^{\circ}$  flaps were used.

The upper value was determined to be the greatest angle expected at any time during any two-segment approach with a Boeing 727. The Supplemental Type Certificate (STC) demonstrations were made at this angle. The glide slope angle will be the same that the ILS has for the airport concerned. The values  $2.5^{\circ}$  to  $3.5^{\circ}$  covers all ILS glide slope angles that would be of concern.

The system is capable of flying high on the glide slope with a fixed bias. This was flown during the engineering flight evaluation and was found to have merit, but it will not be used during the on-line flight evaluation.

The lower intersect altitude range was 400 to 800 ft AFL. The nominal value determined by flight evaluation was about 700 ft. The ground noise measurements were made at the high and low values of this range. The two-segment approach profile, resulting from the flight evaluation, was used for the off-line pilot's evaluation and is basically the same as will be used for the on-line pilot's evaluation.

The Stockton, California, profile is shown in figure III-4. The San Francisco and Los Angeles profiles are very similar. The angle of the standard ILS is different, and

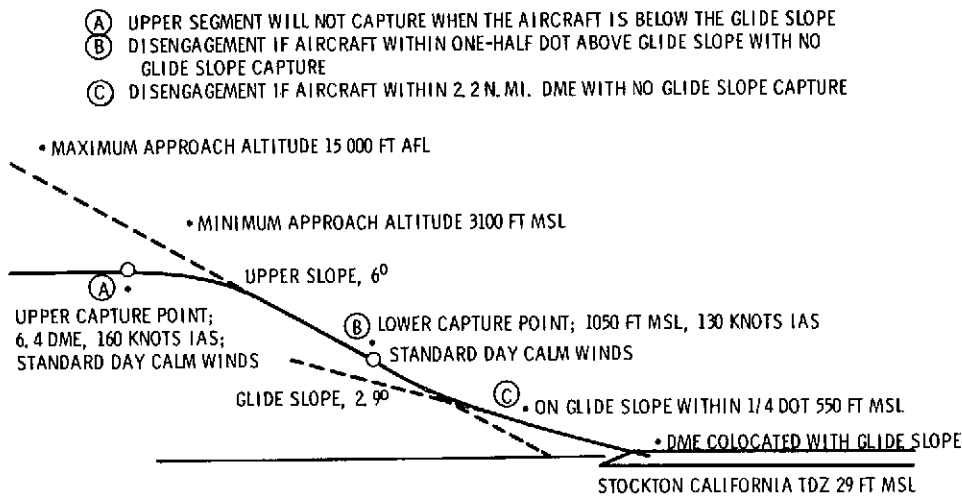


Figure III-4, - Two-segment approach profile used at Stockton, California, resulting from flight evaluation.

this results in a shift of the lower intersect altitude and the lower capture point. The shift with the lowest angle glide slope, flown at the lowest airspeed, is about 100 ft lower. The upper segment can be captured and flown very satisfactory, as high as 15 000 ft AFL. Localizer capture or alignment is not necessary for guidance on the upper segment.

Safety factors were designed into some areas of the profile to increase the flight safety margins for the approach. In the event the baro set, the DME, or the airport elevation panel set malfunctions, the upper segment could be presented prematurely. To prevent a guided approach that would cause a descent below the standard glide slope, the upper segment is prevented from capturing when the aircraft is below the glide slope. If the aircraft is flying the upper segment and gets to within one-half dot deflection above the glide slope, the auto pilot will disengage and the flight director bars bias out of view. This prevents the system from providing guidance that would take the aircraft below the glide slope. If the upper segment is presented late, it would be possible to descend so that the glide slope would be reached very low or not at all. In that case the system will disengage if the aircraft reaches 2.2 nautical miles DME and the glide slope is not captured.

The upper and lower transitions were a key to pilot acceptance. If the pilot can get into and out of the upper segment without any significant change in his flight technique, he should accept the two-segment concept as operationally sound.

The upper transition starts at the upper capture point. If the aircraft is approaching at a high speed or is climbing, the capture point occurs early. If the aircraft is at a low speed or is descending, the capture occurs late. In either case, the aircraft is pitched



nose down slowly and smoothly, such that the upper segment is reached in 500 to 800 ft below the initial altitude at capture.

The lower transition is a smooth, easy pitch change that starts at the lower capture point. The lower capture point will adjust according to the speed at which the aircraft is closing on the glide slope. At high speeds the capture occurs earlier and provides a more gradual pitch change than at low speeds. The result is that the transition seems similar to both pilot and passengers. Passengers do not detect the lower transition. The point at which the glide slope is reached does not shift to any great extent.

The upper segment tracking with its transitions was determined to be very satisfactory. It required no additional pilot skills for routine operation of the Boeing 727-200 aircraft.

The off-line evaluation consisted of a two-phase program to thoroughly familiarize the guest pilot with the two-segment approach, thereby enabling him to evaluate the approach in detail. Phase I was the viewing of an audio-visual package followed by a crew briefing and a 1-hour and 30-minute simulator flight. The simulator involved a syllabus of 11 approaches intermixing the standard ILS with the two-segment ILS under varying weather conditions and operational techniques. Phase II consisted of an aircraft period during which an eight approach syllabus was flown, which again compared the standard ILS with the two-segment ILS in a real world environment.

The expected 90- and 95-effective perceived noise decibels (EPNdB) contours for a Boeing 727-200 aircraft using this two-segment approach procedures are compared in figures III-5 and III-6 with the contours expected as a result of using a standard instrument landing approach. The 90-EPNdB impacted area is reduced during the two-segment approach by 3.7 square miles (67 percent reduction). The 95-EPNdB impacted area is reduced by 1.1 square miles (48 percent reduction).

By increasing the upper intersect altitude, there can be a significant improvement in ground noise outside the outer marker. Altitude of up to 6000 ft AFL can produce noise improvement over large areas in approaching the airport. The aircraft safety is enhanced by staying high in the heavy traffic area, which reduces exposure to many low flying aircraft. It was noticed that the approach with a 6° upper segment could accommodate up to 190 knots (indicated air speed) at 3000 ft AFL to the point of upper segment capture. This speed can be increased as altitude increases up to 250 knots at 6000 ft AFL or higher. The result is lower power setting at higher altitudes and less time at high power settings. This could produce a side benefit of lower fuel consumption of each approach.

The avionics system being evaluated by United Air Lines retains the coupled flight director feature used in the American Airlines program and adds the autopilot coupling so that the pilot can make a two-segment landing with all the aids available for standard approaches.

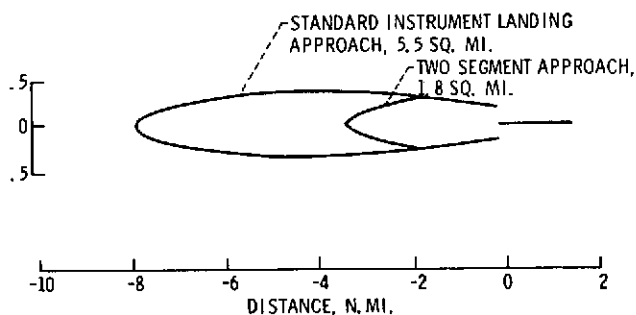


Figure III-5. - 90-EPNdB approach contours for Boeing 727.

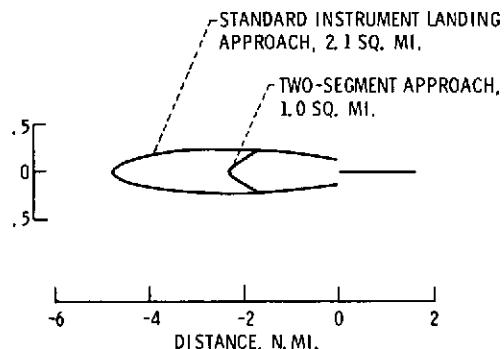


Figure III-6. - 95-EPNdB approach contours for Boeing 727.

United's implementation of the two-segment system stressed adherence to standard procedures to such an extent that one-switch operation and an airport elevation input are the only features that distinguish the two-segment procedure from United's standard ILS procedure.

The special purpose glide slope computer developed by Collins uses a signal from a DME transmitter colocated with the ILS glide slope and barometric corrected pressure altitude to position the aircraft on the upper segment and uses the ILS glide slope deviation to position the aircraft on the lower segment. The two-segment computer also uses altitude rate information from the Central Air Data Computer (CADC) for vertical path damping and airspeed from the CADC to drive an autothrottle.

DME transmitters, colocated with the ILS glide slope, are not standard equipment in an instrument landing system. However, the FAA currently plans to add these facilities at a rate of five in FY 75, 50 in FY 76, 30 in FY 77 and 40 in FY 78. The necessary colocated facilities are available at the airports being used in the program.

Although it is very difficult to estimate the cost of retrofitting United Air Lines fleet of Boeing 727's with this system, it is thought that the cost will be approximately \$31 400, for a dual installation. The \$31 400 assumes \$26 600 for equipment, \$4000 for installation, and \$800 for flight check. Out-of-service and training costs are not included. It is assumed that installation could occur when the aircraft are out of service for other reasons and that training could be incorporated into the normal training and review curriculum.

For several reasons, the present program is providing a much broader basis for evaluating the feasibility of the two-segment approach than in previous programs. First, the avionics have been designed, built, and environmentally tested to FAA Technical Standard Order specifications. The system performs internal selfchecks and, in the event of a failure, provides the pilot with a warning similar to warnings provided in the event of a failure during an ILS approach. Second, the procedure and system have

been tested both in the simulator and in flight under a wide variety of operational conditions. Approaches have been made under instrument flight conditions; in the presence of tail winds, wind shears, and turbulence; at dusk and at night; and at several airports including Los Angeles and San Francisco. Third, over 50 pilots have participated in the off-line pilot evaluation: 15 line pilots representing ALPA and APA, 19 management pilots from the different airlines, 11 FAA pilots, five engineering test pilots, and one USAF pilot. Finally, a broader spectrum of line pilot reactions will be obtained as a result of the in-scheduled service evaluation, which begins in late April 1973 and lasts through October 1973. This will be the first time a two-segment guided approach system has been placed into routine line service. During this period it is expected that over 96 crews will evaluate the system and that over 500 two-segment approaches will be made.

#### STEP B: DEVELOPMENT AND FLIGHT EVALUATION OF TWO-SEGMENT AVIONICS USING THREE-DIMENSIONAL AREA NAVIGATION FOR GUIDANCE IN A DC-8-61

United Air Lines and the Collins Radio Company initiated work, under contract with NASA, on this program in December 1972. The program objectives are to determine the operational feasibility of modifying a three-dimensional area navigation system to provide the two-segment approach capability and to evaluate the two-segment approach in a DC-8-61 aircraft in regular scheduled service.

The program contains the same basic phases as the Boeing 727 evaluation covered in STEP A. However, the avionic concept and aircraft characteristics are substantially different.

In this step an existing area navigation system will be modified to include the two-segment capability. An inherent advantage of this concept is that, if the aircraft is equipped with an area navigation system, a modification to the system represents an inexpensive way of incorporating the two-segment approach capability. A second advantage is that the system can be used to make precision approaches to ILS equipped runways without requiring a colocated DME transmitter facility. The system can also be used to make nonprecision noise abating approaches into non-ILS equipped runways.

The Boeing 727 aircraft used in STEP A is particularly well suited for the two-segment approach. It has relatively high drag in the landing configuration and requires positive thrust component to come down the  $6^{\circ}$  glide slope at reference velocity. It is also equipped with relatively new and complete avionic systems so that the two-segment guidance interface with the autopilot and flight director is straight forward.

On the other hand, the McDonnell-Douglas DC-8 has relatively little drag in the landing configuration and requires near idle thrust to come down a  $6^{\circ}$  glide slope at

reference velocity. In addition to the low drag characteristics, the DC-8 has an autopilot older than the Boeing 727 autopilot. Even though preliminary flight tests indicate that the DC-8 autopilot can follow the two-segment guidance command, the interface between the two-segment guidance system and the autopilot may require more extensive modifications than are required on the Boeing 727. For these reasons, it is the opinion of the airlines, the FAA, and the pilots that the two-segment evaluation must be conducted in the DC-8 in order to establish the envelope of acceptable two-segment approach profiles for the fleet of commercial aircraft.

Although the DC-8 is more difficult to adapt to the two-segment approach, the expected noise benefits are significant. The 90- and 95-EPNdB contours for a DC-8-61 aircraft during a  $6^{\circ}/3^{\circ}$  two-segment approach with a 690-ft intercept altitude are compared in figures III-7 and III-8 with noise contours estimated for a standard instrument landing approach. The 90-EPNdB impacted area is reduced by 6.3 square miles (54 percent reduction), and the 95-EPNdB impacted area is reduced by 3.3 square miles (50 percent reduction).

Cost estimates to provide a fleet of aircraft already equipped with area navigation with the two-segment capability have not yet been worked out in detail. However, the cost will be substantially less than required to retrofit with the special purpose glide slope computer system. An estimate of this cost is \$9000, which includes equipment and installation charges. Out-of-service costs and training costs are not included. It is assumed that installation could occur when the aircraft are out of service for other reasons and that training could be incorporated into the normal training and review curriculum. If the two-segment capability is provided as a part of the area navigation package prior to installation, it appears that the added cost could become quite small.

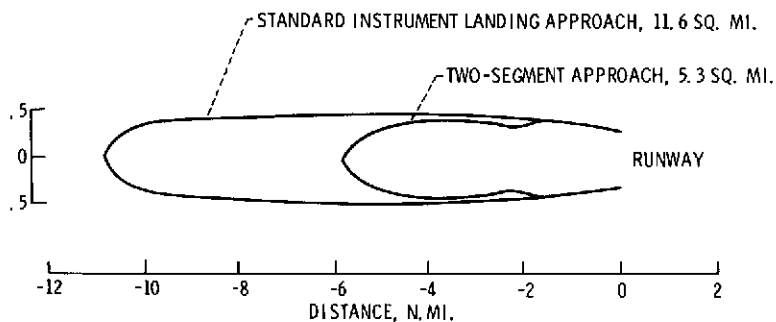


Figure III-7. - 90-EPNdB approach contours for DC-8.

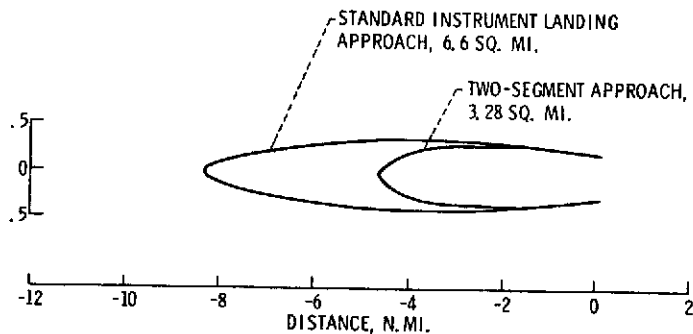


Figure III-8. - 95-EPNdB approach contours for DC-8.

### STEP C: STUDY TO DETERMINE THE APPLICABILITY OF THE TWO-SEGMENT APPROACH TO ADDITIONAL JET TRANSPORTS

The preceding steps are aimed at determining the operational feasibility of the two-segment approach for only two aircraft types. The purpose of this step is to extrapolate the results of these flight programs to cover the McDonnell-Douglas DC-9 and DC-10 and the Boeing 707, 737, and 747 jet transports by an analytical and simulation program.

Contracts will be awarded to Boeing and McDonnell-Douglas Aircraft companies in FY 73 to make a preliminary determination of the approach profiles that would achieve maximum noise abatement while maintaining adequate safety margin and pilot acceptance for their different aircraft. These feasibility studies will not include flight simulations.

Contracts will then be awarded to an airline contractor (or contractors) in FY 74 to conduct a simulation study wherein the operational feasibility of making two-segment approaches in these aircraft will be examined in detail. These studies will look at the effect of extreme wind shear, pilot abuses, and system failures on the safety of the procedure.

### STEP D: STUDY TO DETERMINE THE SUITABILITY OF THREE-DIMENSIONAL AREA NAVIGATION TO PROVIDE VERTICAL GUIDANCE

An analytical study will be conducted to determine the requirements on the location of the ground navigational aids used as inputs to the airborne navigation equipment in order to provide sufficient accuracy for two-segment guidance. The study will also define procedures that can be used to flight check the adequacy of existing ground navigational aids for establishing the upper segment guidance at individual airports.

It is expected that this study will be conducted by the FAA in conjunction with their existing program aimed at defining area navigation requirements.

#### STEP E: STUDY TO DETERMINE THE IMPACT OF THE TWO-SEGMENT APPROACH ON ATC

Aircraft making two-segment approaches will have to mix with aircraft making standard ILS approaches. In addition, it appears that two-segment approaches for different aircraft types will require different upper segment glide slopes. A study will be conducted to determine the impact on ATC of intermixing different approach profiles in the terminal area. It is expected that this study will be conducted by the FAA.

#### OTHER TECHNIQUES FOR NOISE ABATEMENT

##### FLIGHT TEST OF NOISE ABATEMENT APPROACHES USING A MICROWAVE LANDING SYSTEM

By the end of the FY 73 considerable expertise and understanding will have developed with respect to the usefulness of the noise abatement operational procedures when flying the landing approach pattern using the conventional NAVAIDS, that is, ILS, DME, and VORTAC. It is hoped that the FY 73 program and the anticipated follow-on programs for FY 74 will provide sufficient momentum to carry noise abatement procedures using conventional ground NAVAIDS into practice in the airlines. Beyond 1974, however, the question arises as to the impact of the microwave landing system, being developed under FAA contract, on the noise abatement flight procedures. In this respect, no real problems are anticipated in flying noise abatement procedures using the microwave landing system. However, it is almost inevitable, based on past flight test experience, that certain unanticipated problems will surface.

Therefore, a flight test program is planned wherein noise abatement approaches are flown using a microwave landing system in an attempt to take advantage of the full capability of this system and to expose problems that could influence the microwave landing system design. Tests conducted in FY 74 should provide results soon enough to influence the preliminary design and development of the microwave system.

The basic objectives of this program are to determine how to best use the unique capabilities of the microwave landing system for noise abatement and to determine if there are any navigation, guidance, control, and operational problems associated with this type of system.

## FLIGHT EVALUATION OF CURVED APPROACHES FOR NOISE ABATEMENT

Area navigation potentially provides the capability of flying the aircraft along curved approach paths in order to avoid noise sensitive areas. A simulation and flight program is planned, for FY 74 or FY 75, to determine the operational feasibility of using this technique in conjunction with the two-segment approach. The program will be largely conducted in-house and will include analysis, simulation, and flight test. A brief description of the effort planned in these phases follows:

In this phase, the necessary steering signals will be defined and presentation to the pilot will be evaluated. Pilot workload and ability to fly these approaches will offer the greatest obstacle. A principal purpose of the simulation will be to determine the amount of automation required to keep the workload at a level comparable with that required during a standard instrument approach. The effects of winds, wind shears, and pilot abuses will be evaluated. Flight tests will be conducted using the NASA research Boeing 737 aircraft in the Terminal Configured Vehicle and Avionics Program at the NASA Langley Research Center.

## NOISE ABATEMENT USING DECELERATING APPROACHES

Two modifications to the standard approach procedure can be proposed for reducing the noise. One consists of flying a steeper-than-standard approach path (i. e., two-segment approach), which increases the aircraft's altitude over the noise sensitive area and reduces the thrust used in the approach. The other is to make a decelerating approach on a standard glide slope with the engines at idle power. In this method, the aircraft begins the approach at relatively high airspeed and then slowly decelerates to the landing speed, using the kinetic energy as a power source to overcome the drag forces. A third method is also possible by combining the two.

If we assume that the approach is flown along the standard ILS glide slope, then, in principle, the decelerating approach can be started at any point on the ILS beam. The single most important variable in a decelerating approach is the airspeed of the aircraft at the starting point. This airspeed must be chosen such that the aircraft can fly safely from the outer marker to a desired point with all engines operating at minimum permissible thrust, with arrival at the specified point with full flaps, and with the desired landing speed. Assuming the aircraft arrives at the starting point with the proper airspeed, it begins its gliding and decelerating flight along the ILS beam while either the pilot or an automatic landing system maintains the aircraft's flight along the beam. As the aircraft is slowly decelerating, the flaps are extended according to a computed schedule. The novelty of the proposed technique lies in the use of flap angle modulation rather than

the more commonly encountered thrust modulation as a method of deceleration control. If the proper airspeed was selected at the starting point and if the flaps are extended at the proper rate, the landing speed and the full-flap configuration will be reached close to the interception of the glide path with the runway or at any other point along the glide path designated at the terminal point of the deceleration. Since this procedure allows thrust to be maintained at the lowest possible value throughout the approach, engine noise is kept to a minimum. There are safety questions related to this approach because of the time required to spool up the engines if a go-around is required.

## ANALYSIS

In this phase, the principle objectives are to make a preliminary evaluation of the profile to be flown; that is, whether the decelerating approach should be flown along the standard ILS glide slope or along a two-segment glide slope; perhaps along a  $3\frac{1}{2}^{\circ}$  to  $4\frac{1}{2}^{\circ}$  glide slope and then about a mile from the runway threshold transition to the normal ILS glide slope. In this phase, the optimum speed profile, flap extension schedule, transition point, flight director requirements for aided manual guidance, guidance laws and interfaces with autopilot and autothrottle for automatic approach, as well as the navigation requirements must be determined.

## Piloted Simulation

Pilot workload and ability to fly these trajectories will offer the greatest obstacle. Considerable automation will be required to keep workload from increasing beyond that of standard approaches. A principal purpose of the simulation will be to determine the minimum level of automation needed to keep the workload reasonable. The simulation program will also evaluate cockpit displays, check out flight director guidance laws and automatic guidance, determine missed approach procedures, study the effect of gusts and wind shears, and define pilot procedures for the manual approach.

## Flight Test

It is planned that the flight test program will be conducted using NASA Boeing 737 aircraft in the Terminal-Configured Vehicle and Avionics Program. The main objective of the flight test phase will be to refine the operation of the "decelerating approach" system, further develop the operational procedures, and assess system performance in



the actual flight environment. The final objective of course, is to reduce this experimental approach technique to practice.

## AERODYNAMIC NOISE

Recent computations and measurements have suggested that there may be an aerodynamic noise floor in the approach and landing configuration of large jets about 10 PNdB below the FAR Part 36 noise level. Operational procedures such as the two-segment and curved ground track approaches, which increase the separation of the observer and the aircraft, are effective at reducing the impact of aerodynamic as well as engine noise. The aerodynamic noise varies as a high power of the flight speed. Therefore, the decelerating approach, which approaches at higher speed, would have a higher aerodynamic noise floor.

In order to obtain better data on the aerodynamic noise floor and understand the relationship between aerodynamic noise and engine noise and the different types of noise abatement approaches (the steep glide slope, the two-segment approach, the curved ground track, and decelerating approach) NASA Ames is planning a flight test program with the NASA CV-990, four-engine jet aircraft and possibly other aircraft.

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## IV - MILITARY ASPECTS

In discussing the military aspects of noise technology, NASA's intent is specifically not to review or comment on the military's noise research and development programs. Rather, it is to present the major cooperative programs underway between the DOD and NASA and to point out NASA's objectives and interest in participating jointly with the military services. In general, at least three major benefits accrue to the Nation from combined efforts of this type:

- (1) NASA noise technology applicable to and needed by military programs is available in a timely way.
- (2) Civilian derivatives of military machines, environmentally acceptable with regard to noise and pollution, may be more economically and expeditiously phased into the commercial field.
- (3) NASA keeps the touchstone of practical hardware in its long range technology effort.

### TURBINE ENGINE PROGRAMS

The Air Force is in the process of procuring a demonstration model of an Advanced Technology Engine (ATE) to insure that the technology of high performance, high bypass ratio engines is sufficient and ready for application, this decade and the next, to subsonic military aircraft. The engine generally is in the 20,000-pound plus thrust category, will have a high thrust to weight ratio, good specific fuel consumption and, with minimum modification, contain those qualities attractive to civil propulsive systems. The potential for the application of a derivative of this engine to commercial transport is significant, and the Air Force and NASA have recognized that a cooperative effort between the two agencies is desirable and necessary. Accordingly, a close relationship, formally documented, exists between NASA and the Air Force during this program development to insure that specific features are designed into the engine to meet environmental requirements. The Air Force obviously cannot compromise engine performance unduly to meet civil standards. However, acceptable compromises and/or trade-offs in performance are being considered along with design features that minimize the modifications that would be needed to provide an environmentally acceptable ATE derivative engine. These considerations are important and recognized factors in the Air Force program.

Technology demonstrator programs such as the Advanced Technology Engine are intended to explore and develop specific engine systems based on credible, full-scale advanced technology hardware. Potential military application for the ATE include both short-haul and long-haul logistics transports and perhaps other support aircraft. The cycle and design characteristics are 20,000- to 25,000-pounds thrust, moderately high bypass ratio ( $\sim 7$ ), low specific fuel consumption, improved maintainability through modular maintenance concepts, and reduced bare engine noise and emissions. The performance expected from this engine cycle makes it particularly attractive for civil conventional takeoff and landing aircraft. NASA's primary objective in working with the Air Force is the establishment of those design features for minimizing the environmental impact of the operational engine both in the military and civilian versions. Based on its propulsion noise research and technology programs, NASA can help predict the performance tradeoffs associated with low noise and emissions and determine which design features are in the national interest, particularly with regard to the ATE demonstrator civil derivative potential.

Powered lift technology for application to civil high performance jet transport aircraft constitutes an important objective of NASA's propulsion research. Quiet, clean propulsion systems for this application present an even greater challenge than the more conventional engine like ATE, primarily because of the very stringent noise and pollution requirements associated with expected operation close to heavily populated areas. A very important part of NASA's powered lift technology program is the Quiet, Clean, Short-Haul Experimental Engine (QCSEE) program. Compared with the ATE, this engine will probably have a much higher bypass ratio (15), may have variable rather than fixed pitch fan blades, may be geared rather than have direct drive, and will have very low exit velocities (700 ft/sec) to meet the low noise goals for civil powered lift aircraft. Although the fan/low pressure turbine spool differs greatly from the ATE, it is quite possible that the engine core can be common to the two programs, perhaps with relatively minor modification. As the two programs progress, every effort will be made to capitalize on the military development of the ATE core and to apply it to the QCSEE program to reduce risks and costs. The QCSEE program will begin with that intent and will continue unless that course proves technically impossible.

### STOL AIRCRAFT PROGRAMS

The Advanced Medium STOL (AMST) program is being conducted by the Air Force to design and fabricate two different STOL airplanes to test and evaluate the worth of such aircraft in a modernized tactical airlift fleet. NASA is actively supporting this program to generate quiet propulsive lift technology and design data for civil STOL, RTOL, and CTOL transport. Prime NASA objectives in this combined program are

directed toward high angle takeoff and approach paths (permitted through the use of propulsive lift) to provide community noise reduction and relief of airport congestion (both air and ground movement of aircraft). Further, NASA's research using this military aircraft will establish a technical foundation for the certification, operation, and regulation of civil propulsive lift transports.

Complete satisfaction of these significantly different objectives imposes diverse vehicle requirements that clearly would result in completely different aircraft designs. However, a very significant portion of the NASA objectives can be satisfied through this program. For example, propulsive lift flight research requires variations in noise reduction, lift-coefficient, thrust-weight ratio, aircraft loadings, stability and control systems, and high lift systems considerably broader than those achievable through the point-design prototypes. Nevertheless, these prototypes can provide the baseline technical and operational data within certain ranges of parametric interest. NASA participation in this program is aimed not only at supporting the military objectives wherever possible but also at using this aircraft in a test program to demonstrate the viability of a civil STOL transport that is environmentally acceptable to surrounding communities.

#### ROTORCRAFT PROGRAMS

Two research programs, being conducted jointly with the Army, have a direct bearing on noise abatement and noise research.

The first, the Tilt Rotor Research Aircraft embodies the desirable hover characteristics of the turboprop aircraft through tiltable rotors mounted at the wing tips. The low disk loading rotors, the absence of a tail rotor, the reduced power required because of wing lift, and the more efficient rotor performance in the cruise configuration combine to offer a substantial noise reduction potential. A goal of 90 perceived noise decibels (PNdB) along a sideline distance of 500 feet (ft) for the most critical flight condition has been established.

The Army is concerned with cruise flight noise and the resulting detection times. Comparison of the noise of the tilt-rotor aircraft with that of a single rotor helicopter, both in cruise and at low altitude, promises a reduction from around 125 to about 65 PNdB with the corresponding detection time reduced from that of 36 to 72 seconds to about 5 to 10 seconds.

Objectives of the program include:

- (1) The exploration, through flight research, of current technology of interest to the aircraft community for the development of useful, quiet, easily maintainable commercial or military V/STOL tilt-rotor aircraft, particularly by verifying rotor/plyon/wing dynamic stability and aircraft performance over the entire envelope

- (2) The investigation of the effects of tilt rotor disk and tip speed on downwash and noise and the impact on hover mode operations.

Other research objectives include the development and evaluation of methods and procedures for efficient near-terminal operation to reduce congestion and noise and to increase safety, and the evaluation of potential benefits of applying tilt rotor aircraft capabilities to various Army Air Mobility missions.

The Rotor Systems Research Aircraft, the second program, is being designed and developed to serve as a flight research test bed. The aircraft will essentially be a compound helicopter with a wing and auxiliary propulsion to permit rotor testing throughout a wide range of operating conditions.

Today's helicopter missions entail hovering, low-speed flight, and high-speed forward flight. The operation of a rotor in forward flight creates asymmetrical flow conditions finally resulting in retreating blade stall and/or advancing blade compressibility effects. These generally unsteady aerodynamic flows are a source of vibratory loads and aerodynamic noise. There are, however, new rotor concepts in various stages of development that have the potential of alleviating some of these limitations, thereby enhancing the helicopter as a commercial transportation system and as a military vehicle. The variable geometry rotor offers a favorable azimuthal distribution of the blades that may reduce noise and vibration. New tip shapes and blade planform designs are considered as potential improvements in aerodynamic efficiency and reduced noise.

The Rotor Systems Research Aircraft will be used for the investigation of the rotor system intended to demonstrate low-noise characteristics. The design of the vehicle will consider noise suppression equipment on engine inlet nacelles and exhaust ducts, gear boxes, and the antitorque device in order to prevent masking of the rotor system noise with noise from other aircraft systems and subsystems. An external noise level of not more than 95 PNdB at the 500 ft sideline in takeoff and landing and, excluding main rotor noise, not more than 89 PNdB at any point 500 ft from the aircraft when operating as a conventional helicopter at speeds up to 150 knots has been established.